



Calhoun: The NPS Institutional Archive

Theses and Dissertations

Thesis Collection

1984

Development of criteria for automatic steering.

Spyromilios, Pericles Kyritsis

<http://hdl.handle.net/10945/19255>



Calhoun is a project of the Dudley Knox Library at NPS, furthering the precepts and goals of open government and government transparency. All information contained herein has been approved for release by the NPS Public Affairs Officer.

**Dudley Knox Library / Naval Postgraduate School
411 Dyer Road / 1 University Circle
Monterey, California USA 93943**

<http://www.nps.edu/library>

DUDLEY KNOX LIBRARY
NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA 93943

NAVAL POSTGRADUATE SCHOOL

Monterey, California



THESIS

DEVELOPMENT OF CRITERIA FOR AUTOMATIC
STEERING

By

Pericles Kyritsis-Spyromilios

December 1984

Thesis Advisor:

G.J. Thaler

Approved for public release; distribution is unlimited.

T223457

| REPORT DOCUMENTATION PAGE | | READ INSTRUCTIONS BEFORE COMPLETING FORM |
|---|-----------------------|---|
| 1. REPORT NUMBER | 2. GOVT ACCESSION NO. | 3. RECIPIENT'S CATALOG NUMBER |
| 4. TITLE (and Subtitle) Development of Criteria for Automatic Steering | | 5. TYPE OF REPORT & PERIOD COVERED Master's Thesis; December 1984 |
| | | 6. PERFORMING ORG. REPORT NUMBER |
| 7. AUTHOR(s) Pericles Kyritsis-Spyromilios | | 8. CONTRACT OR GRANT NUMBER(s) |
| 9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93943 | | 10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS |
| 11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93943 | | 12. REPORT DATE December 1984 |
| | | 13. NUMBER OF PAGES 121 |
| 14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) | | 15. SECURITY CLASS. (of this report) UNCLASSIFIED |
| | | 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE |
| 16. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution is unlimited. | | |
| 17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report) Approved for public release; distribution is unlimited. | | |
| 18. SUPPLEMENTARY NOTES | | |
| 19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Regular Seas, Irregular Seas, Controller Design, Encounter Frequency, Encounter Angle, Yaw, Rudder, BOXPLX | | |
| 20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The effect of added resistance due to steering on a high-speed containership is propulsion reduction. Limitation on the propulsion losses can be achieved by a properly designed controller, which minimizes the rudder activity as well as providing desired overseas heading. A computer program, simulating a cascade configuration of the SL-7 high-speed containership along with a specific | | |

controller was coupled to a function minimization subroutine as well as a sea state generator subroutine in order to minimize a performance criterion.

The entire model was tested for a fixed speed, several encounter frequencies, several encounter angles in calm waters and in a seaway as well.

Approved for public release; distribution is unlimited.

Development of Criteria for Automatic Steering

by

Pericles Kyritsis-Spyromilios
Lieutenant, Hellenic Navy
B.S., Naval Academy of Greece, 1975

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ENGINEERING SCIENCE

from the

NAVAL POSTGRADUATE SCHOOL
December 1984

ABSTRACT

The effect of added resistance due to steering on a high-speed containership is propulsion reduction. Limitation on the propulsion losses can be achieved by a properly designed controller, which minimizes the rudder activity as well as providing desired overseas heading.

A computer program, simulating a cascade configuration of the SL-7 high-speed containership along with a specific controller was coupled to a function minimization subroutine as well as a sea state generator subroutine in order to minimize a performance criterion.

The entire model was tested for a fixed speed, several encounter frequencies, several encounter angles in calm waters and in a seaway as well.

TABLE OF CONTENTS

| | | |
|--|---|-----|
| I. | INTRODUCTION | 11 |
| II. | DESCRIPTION OF COMPUTER MODELS | 13 |
| III. | STEERING PERFORMANCE CRITERION | 17 |
| IV. | CONTROLLER DESIGN FOR REGULAR SEAS | 19 |
| V. | IRREGULAR SEAS-CONTROLLER DESIGN | 50 |
| VI. | ADAPTIVE CONTROL | 58 |
| | A. STRUCTURE | 58 |
| | B. SEARCH ALGORITHM | 59 |
| | C. ADVANTAGES | 60 |
| | D. DISADVANTAGES | 61 |
| VII. | CONCLUSIONS AND RECOMMENDATIONS | 63 |
| | A. CONCLUSIONS | 63 |
| | B. RECOMMENDATIONS FOR FUTURE STUDY | 64 |
| APPENDIX A: DETERMINATION OF NOMOTO THIRD ORDER MODEL-BOXPLX | | 65 |
| APPENDIX B: CONTROLLER DESIGN | | 86 |
| | A. CONTROLLER "C" | 86 |
| | B. CONTROLLER "B" | 88 |
| | C. CONTROLLER "A" | 91 |
| | D. CODING OF THE EQUATIONS | 93 |
| APPENDIX C: RESPONSE OF THE SYSTEM FOR REGULAR SEAS . . | | 95 |
| APPENDIX D: DETERMINATION OF OPTIMAL CONTROLLER PARAMETERS FOR IRREGULAR SEAS | | 104 |

| | |
|---|-----|
| APPENDIX E: RESPONSE OF THE SYSTEM FOR IRREGULAR SEAS..... | 112 |
| LIST OF REFERENCES..... | 119 |
| INITIAL DISTRIBUTION LIST..... | 120 |

LIST OF TABLES

| | | |
|-----|---|----|
| 1. | Nomoto Third Order Model | 16 |
| 2. | Weighting Factors | 18 |
| 3. | Sea State Vs Wave Height | 20 |
| 4. | Controller C For 0° Encounter Wave Angle | 23 |
| 5. | Controller C For 30° Encounter Wave Angle | 24 |
| 6. | Controller C For 60° Encounter Wave Angle | 25 |
| 7. | Controller C For 90° Encounter Wave Angle | 26 |
| 8. | Controller C For 0° Encounter Wave Angle | 27 |
| 9. | Controller C For 30° Encounter Wave Angle | 28 |
| 10. | Controller C For 60° Encounter Wave Angle | 29 |
| 11. | Controller C For 90° Encounter Wave Angle | 30 |
| 12. | Controller C for Different Encounter Wave Angle . . | 52 |

LIST OF FIGURES

| | | |
|------|--|----|
| 2.1 | Block Diagram of Ship and Control System | 13 |
| 2.2 | Determination of Nomoto Third Order Model | 14 |
| 4.1 | Controller C | 20 |
| 4.2 | Yaw Vs Time, Sea State 4. Encounter Frequency 0.2 rads per sec, Encounter Angle 30° | 31 |
| 4.3 | Yaw Vs Time, Sea State 4. Encounter Frequency 0.4 rads per sec, Encounter Angle 30° | 32 |
| 4.4 | Yaw Vs Time, Sea State 4. Encounter Frequency 0.6 rads per sec, Encounter Angle 30° | 33 |
| 4.5 | Yaw Vs Time, Sea State 4. Encounter Frequency 0.75 rads per sec, Encounter Angle 30° | 34 |
| 4.6 | Yaw Vs Time, Sea State 4. Encounter Frequency 1.5 rads per sec, Encounter Angle 30° | 35 |
| 4.7 | Yaw Vs Time, Sea State 4. Encounter Frequency 0.2 rads per sec, Encounter Angle 60° | 36 |
| 4.8 | Yaw Vs Time, Sea State 4. Encounter Frequency 0.2 rads per sec, Encounter Angle 90° | 37 |
| 4.9 | Rudder Vs Time, Sea State 4. Encounter Frequency 0.2 rads per sec, Encounter Angle 30° . . | 38 |
| 4.10 | Rudder Vs Time, Sea State 4. Encounter Frequency 0.4 rads per sec, Encounter Angle 30° . . | 39 |
| 4.11 | Rudder Vs Time, Sea State 4. Encounter Frequency 0.6 rads per sec, Encounter Angle 30° . . | 40 |
| 4.12 | Rudder Vs Time, Sea State 4. Encounter Frequency 0.75 rads per sec, Encounter Angle 30° | 41 |
| 4.13 | Rudder Vs Time, Sea State 4. Encounter Frequency 1.5 rads per sec, Encounter Angle 30° . . | 42 |

| | | |
|------|---|----|
| 4.14 | Rudder Vs Time, Sea State 4. Encounter Frequency 0.2 rads per sec, Encounter Angle 60° . . | 43 |
| 4.15 | Rudder Vs Time, Sea State 4. Encounter Frequency 0.2 rads per sec, Encounter Angle 90° . . | 44 |
| 4.16 | Cost Vs T1, Sea State 7. Encounter Frequency 0.2 rads per sec, Encounter Angle 30° | 45 |
| 4.17 | Cost Vs T2, Sea State 7. Encounter Frequency 0.2 rads per sec, Encounter Angle 30° | 46 |
| 4.18 | Cost Vs T3, Sea State 7. Encounter Frequency 0.2 rads per sec, Encounter Angle 30° | 47 |
| 4.19 | Cost Vs T4, Sea State 7. Encounter Frequency 0.2 rads per sec, Encounter Angle 30° | 48 |
| 4.20 | Cost Vs K1, Sea State 7. Encounter Frequency 0.2 rads per sec, Encounter Angle 30° | 49 |
| 5.1 | Yaw vs Time, Sea State 4. Encounter Frequency 0.75 Rads Per Sec, Encounter Angle 30° | 53 |
| 5.2 | Yaw vs Time, Sea State 6. Encounter Frequency 0.75 Rads Per sec, Encounter Angle 30° | 54 |
| 5.3 | Yaw vs Time, Sea State 7. Encounter Frequency 0.75 Rads Per Sec, Encounter Angle 30° | 55 |
| 5.4 | Rudder vs Time, Sea State 4. Encounter Frequency 0.75 Rads Per Sec, Encounter Angle 30° | 56 |
| 5.5 | Rudder vs Time, Sea State 6. Encounter Frequency 0.75 Rads Per Sec, Encounter Angle 30° | 57 |
| 6.1 | Adaptive Control Scheme | 60 |
| 6.2 | Decision Generator | 61 |
| B.1 | Block Diagram of Controller C | 86 |
| B.2 | Block Diagram of Controller B | 89 |
| B.3 | Block Diagram of Controller A | 91 |
| B.4 | General Scheme of Control | 94 |

ACKNOWLEDGMENTS

At the completion of this research the author initially wishes to express his gratitude as well as his personal sincere appreciation to Dr. George J. Thaler for his attentive assistance in all phases of this work.

Furthermore I would like to express my sincere contentment to:

- My father and mother Elefterios and Chaido respectively from where I inherited the desire for education and continuous self improvement.
- Lieutenant Emmanuel Horianopoulos H.N for his cooperation and support in all problems that appeared during the research.
- Lieutenant Vicente Chaves Garcia Jr USN for his support and LCDR Jim Cass USN for providing the sea state generator program.

I. INTRODUCTION

The 1973 oil crisis, where the price of a barrel of oil jumped higher than 210 percent and affected every aspect of the world economy, directly affected the shipping transportation industries. Whereas the price of oil was formerly of modest importance, it became a prime concern. Extensive association to the emerged problem has to do with the design of autopilots for ships, which can minimize propulsive losses caused by added resistance due to steering.

One motivation for the design of an optimum steering controller was the work done by Nomoto and Motoyama who claimed that reduction in propulsion loss could amount to a 1 percent savings in fuel consumption.

For most commercial ships a 1 to 2 percent saving in fuel costs, justifies the expense of fitting an autopilot which has the capability of producing this savings [Ref. 1].

Chapter 2 addresses what type of computer model can be used to represent the ship. Several of these models are investigated, such as simulation from the equations of motion and the Nomoto third order which was developed from the equation of motion.

Chapter 3 addresses the problem of selecting an adequate cost function to represent the added resistance due to steering.

The problem of finding the best controller design to provide a minimum value of added resistance due to steering, for regular and irregular seas, is studied in Chapters 4 and 5 respectively by using as a model of the ship the equations of motion and a function minimization subroutine.

Chapter 6 indicates how the controller parameters can be adjusted in any encounter environmental condition by means of an adaptive control.

Chapter 7 presents the conclusions from the experimental work.

II. DESCRIPTION OF COMPUTER MODELS

The most accurate model which can represent the ship/steering dynamics is the model which is based upon the equations of motion as defined by series expansion including all terms (both linear and nonlinear).

Using experimentally measured hydrodynamic coefficients, for the SL-7 high speed containership, a computer program was developed in order to provide a computer simulation for the ship. Figure 2.1 shows the block diagram and the computer program can be found in Appendix A [Ref. 2,3].

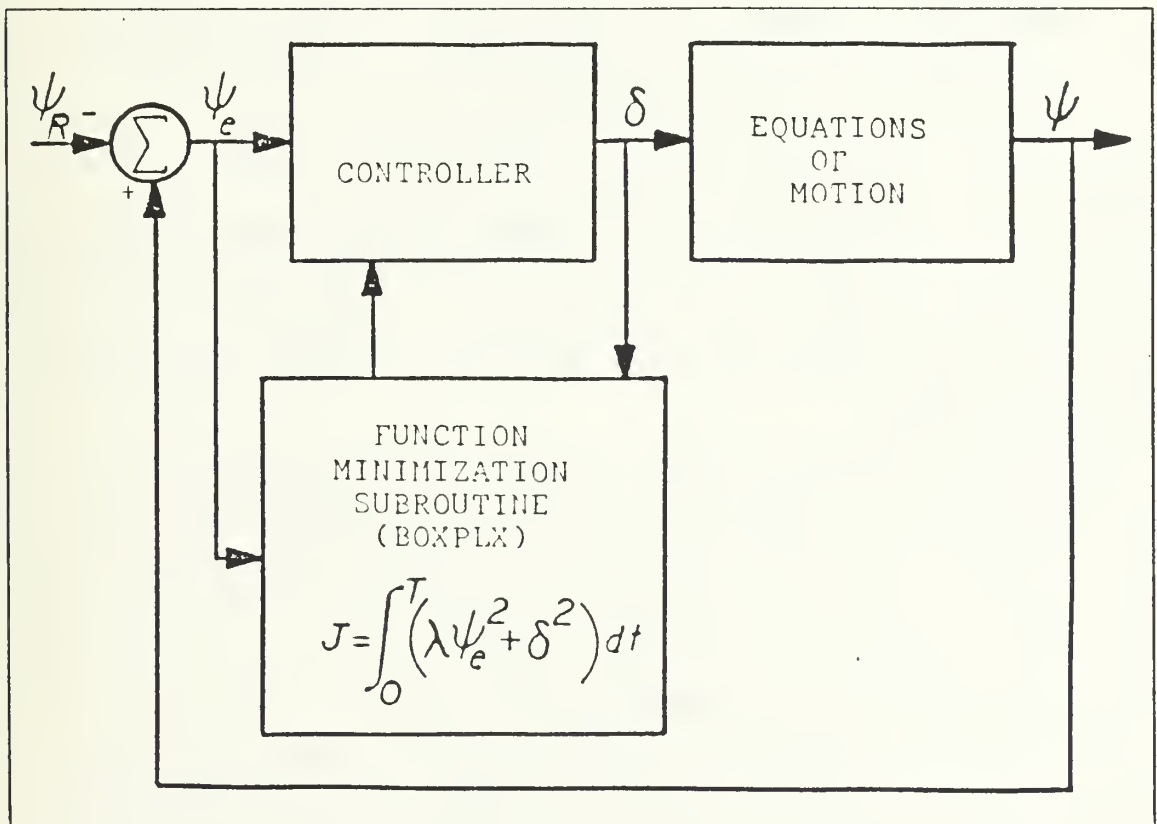


Figure 2.1 Block Diagram of Ship and Control System

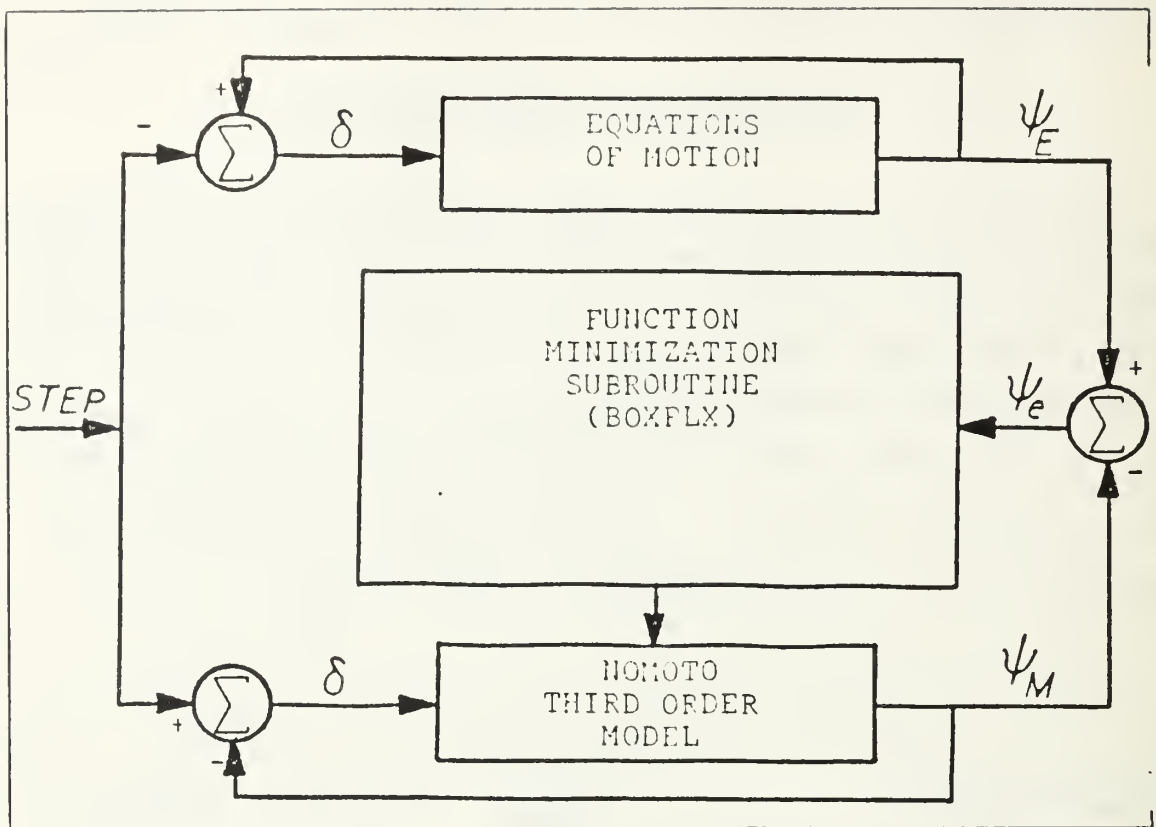


Figure 2.2 Determination of Nomoto Third Order Model

As a next choice, from the equations of motion we derive the Nomoto third order transfer function. Figure 2.2 shows the block diagram.

Using the scheme of Figure 2.2 which includes the function minimization subroutine with both yaw and sway equations, with the linear terms only we obtain the appropriate coefficients of the Nomoto third model. (Including in the equations of motion nonlinear terms we can see that the perturbations were small enough).

The function minimization subroutine used was BOXPLX, which was programmed by R. Hilleary. The task of the already mentioned subroutine is to find the minimum of any function and is subjected to explicit constraints of the variables or

implicit constraints on functions of the variables. In addition it can handle a maximum of 25 variables [Ref. 4].

The extracted results were very close to the results we got by the analytic solution and are tabulated below only for 16, 23 and 32 knots.

TABLE 1
Nomoto Third Order Model

| SPEED KNOT FT/SEC | MK | | MZ | | MP1 | | MP2 | |
|----------------------|--------|--------|--------|--------|--------|--------|--------|---------|
| | CALC. | COMP. | CALC. | COMP. | CALC. | COMP. | CALC. | COMP. |
| 16 27 | 0.0738 | 0.0738 | 22.567 | 22.567 | 12.945 | 12.945 | 107.58 | 107.583 |
| 23 38.81 | 0.1067 | 0.1053 | 15.675 | 15.199 | 9.014 | 8.696 | 75.13 | 73.893 |
| 32 54 | 0.1476 | 0.1477 | 11.29 | 11.283 | 6.5 | 6.469 | 53.76 | 53.793 |

III. STEERING PERFORMANCE CRITERION

Studying the literature, one can see many approaches to the problem of optimizing an automatic ship steering controller for maximum reduction in fuel consumption. Since added resistance is directly related to both rudder activity and yawing motion we can express a measure of this added resistance given as a performance criterion with the formula:

$$J = \frac{1}{T} \int_0^T (\lambda \psi_e^2 + \delta^2) dt \quad (3.1)$$

Where:

- Delta (δ) = rudder angle
- Psi (ψ_e) = yaw angle
- Lambda (λ) = weighting factor

This formula defines an approximate drag due to steering for small amplitude oscillations about a steady-state pivot point of the ship during yawing at the natural frequency of the closed-loop ship/steering system. (About 0.05 rad/sec for the SL-7 containership). It is also convenient for shipboard use because yaw error and rudder angle can be easily measured.

During this study the values for the weighting factors are taken from R. E. Reid's work for the high-speed containership SL-7 [Ref. 5].

TABLE 2
Weighting Factors

| Ship's Speed,Knots | Lambda |
|--------------------|--------|
| 16 | 16.796 |
| 23 | 8.128 |
| 32 | 4.2 |

In Table 2 weighting factors for the operating range of the ship are tabulated.

IV. CONTROLLER DESIGN FOR REGULAR SEAS

Our goal now, is to estimate the system's performance in a seaway. To accomplish the above task first we must determine a suitable representation of the external disturbances on the ship by the sea. This can be done, since a sufficiently accurate computer ship model and a steering performance criterion have been defined.

It can be postulated that a sufficiently accurate model of the seaway itself, is a representative modeling of forces and moments exerted on the ship [Ref. 6,7,8]. An explanation of what a sea comprises, and how predicted or observed sea states can be analyzed to determine the forces and motions of a body in a sea was studied by Michael [Ref. 9].

In this chapter we will use as a seaway representation the regular sea model in which the forces on the ship [Ref. 10], have the form:

$$W_h \cdot R_e \cdot \cos(\omega_e t + \vartheta_i) \quad (4.1)$$

Where:

- R_e =exciting force
- ω_e =encounter frequency
- W_h =wave height
- ϑ_i =phase angle

Values for the exciting force () for different encounter angles and different encounter frequencies as well, were taken from [Ref. 3]. Table 3 shows the correspondence between wave height and sea state which were used in this work.

The controller used in the present study is shown in Appendix B and its form is repeated here in Figure 4.1 .

TABLE 3
Sea State Vs Wave Height

| Sea State (Beaufort scale) | Wave Height (in feet) |
|-------------------------------|--------------------------|
| 1 | 4.0 |
| 2 | 4.5 |
| 4 | 5.5 |
| 6 | 10.0 |
| 7 | 17.5 |

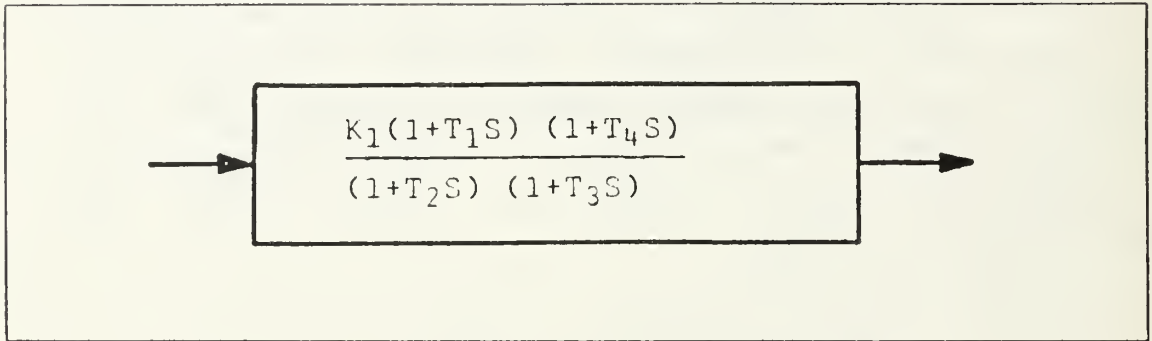


Figure 4.1 Controller C

Values for the optimal gains for the above controller and values for the cost J as well, are shown below in Tables 4,5,6,7,8,9,10,11

These values were obtained using:

- Sea states 1-2-4-6-7 (Beaufort scale).
- Encounter angles 0°-30°-60°-90°.
- Encounter frequencies 0.2-0.4-0.6-0.75-1.5 rad per sec.
- Constant speed 23 knots.

A careful analysis of the extracted results lead us to conclude:

- The maximum deviation of controller parameter values occurred at 0.4 rad per sec encounter frequency for all used encounter angles and sea states.
- For the same encounter frequency, for all encounter angles studied, the controller parameter values increasing smoothly as the sea state increases.
- For all encounter frequencies and for specific encounter angles, we observe that the cost increases at higher sea states.
- For 0.4 rad per sec encounter frequency the cost changes rapidly for sea state 6 and 7 as we move through the encounter angles.
- For the same encounter angles and sea states the cost decreases at higher encounter frequencies.
- For all encounter angles and encounter frequencies the maximum cost occurred for sea state 7.
- The cost had it's maximum value for encounter angle 90° and encounter frequency 0.4 rad per sec.

Furthermore in order to obtain the behavior of the rudder and yaw motion of the ship, transient response plots were obtained for controller 'C' at ship's speed 23 knots, different sea states and encounter angles as shown in Figures 4.2 through 4.15

These plots were obtained using the program of Appendix C.

From these plots it is verified that for the same encounter frequencies and encounter angles, rudder and yaw motion increases in amplitude as the sea states rises.

Finally Figures 4.16, 4.17, 4.18, 4.19, 4.20, show the results of an experiment in which we were changing one controller parameter keeping the rest fixed, and we observed that the cost does not change significantly in the vicinity of the actual value.

Using that as a fact we can postulate that for a specific sailing mode for the controller parameter values high accuracy is not required.

Comparing controller C with controller A it is obvious that the parameter values of controller A vary over wider range.

TABLE 4

Controller C For 0° Encounter Wave Angle

Encounter Frequency 0.2 Rads Per Sec

| | | |
|------------|---------------|---------------|
| Sea State: | 1 | 2 |
| K1= | 1.39999996 | 1.39999996 |
| T1= | 58.2299957 | 58.2299957 |
| T2= | 24.00000000 | 24.00000000 |
| T3= | 10.50000000 | 10.50000000 |
| T4= | 3.00000000 | 3.00000000 |
| Cost J= | 0.6382236E-33 | 0.8077518E-33 |

Encounter Frequency 0.4 Rads Per Sec

| | | |
|------------|---------------|---------------|
| Sea State: | 1 | 2 |
| K1= | 1.39999996 | 1.39999996 |
| T1= | 58.2299957 | 58.2299957 |
| T2= | 24.00000000 | 24.00000000 |
| T3= | 10.50000000 | 10.50000000 |
| T4= | 3.00000000 | 3.00000000 |
| Cost J= | 0.9306967E-35 | 0.1177913E-34 |

Encounter Frequency 0.6 Rads Per Sec

| | | |
|------------|---------------|---------------|
| Sea State: | 1 | 2 |
| K1= | 1.39999996 | 1.39999996 |
| T1= | 58.2299957 | 58.2299957 |
| T2= | 24.00000000 | 24.00000000 |
| T3= | 10.50000000 | 10.50000000 |
| T4= | 3.00000000 | 3.00000000 |
| Cost J= | 0.1868590E-36 | 0.2364934E-36 |

Encounter Frequency 0.75 Rads Per Sec

| | | |
|------------|---------------|---------------|
| Sea State: | 1 | 2 |
| K1= | 1.39999996 | 1.39999996 |
| T1= | 58.2299957 | 58.2299957 |
| T2= | 24.00000000 | 24.00000000 |
| T3= | 10.50000000 | 10.50000000 |
| T4= | 3.00000000 | 3.00000000 |
| Cost J= | 0.1917420E-38 | 0.2426735E-38 |

Encounter Frequency 1.5 Rads Per Sec

| | | |
|------------|---------------|---------------|
| Sea State: | 1 | 2 |
| K1= | 1.39999996 | 1.39999996 |
| T1= | 58.2299957 | 58.2299957 |
| T2= | 24.00000000 | 24.00000000 |
| T3= | 10.50000000 | 10.50000000 |
| T4= | 3.00000000 | 3.00000000 |
| Cost J= | 0.1476825E-38 | 0.1869107E-38 |

TABLE 5
Controller C For 30° Encounter Wave Angle

Encounter Frequency 0.2 Rads Per Sec

| | | |
|------------|--------------|---------------|
| Sea State: | 1 | 2 |
| K1= | 1.7432022 | 1.7434111 |
| T1= | 35.1575165 | 35.0142517 |
| T2= | 22.0137024 | 22.0644684 |
| T3= | 13.5792084 | 13.7818375 |
| T4= | 22.0728760 | 22.1337128 |
| Cost J= | 0.594662E+00 | 0.7502608E+00 |

Encounter Frequency 0.4 Rads Per Sec

| | | |
|------------|---------------|---------------|
| Sea State: | 1 | 2 |
| K1= | 0.2120571 | 0.1997837 |
| T1= | 92.9998932 | 99.9923096 |
| T2= | 24.2121429 | 24.2589569 |
| T3= | 39.9739990 | 39.9999542 |
| T4= | 32.8156433 | 34.0418396 |
| Cost J= | 0.2301481E-02 | 0.2901770E-02 |

Encounter Frequency 0.6 Rads Per Sec

| | | |
|------------|---------------|---------------|
| Sea State: | 1 | 2 |
| K1= | 1.8069019 | 1.7886524 |
| T1= | 1.1657065 | 1.1832294 |
| T2= | 12.4824829 | 13.3286743 |
| T3= | 13.7605896 | 15.5890350 |
| T4= | 9.2525921 | 9.2333460 |
| Cost J= | 0.1797669E-02 | 0.2275771E-02 |

Encounter Frequency 0.75 Rads Per Sec.

| | | |
|------------|---------------|---------------|
| Sea State: | 1 | 2 |
| K1= | 2.2712851 | 2.2712851 |
| T1= | 0.8431141 | 0.8431141 |
| T2= | 24.1657867 | 24.1657867 |
| T3= | 22.2913666 | 22.2913666 |
| T4= | 9.8764191 | 9.8764191 |
| Cost J= | 0.1094168E-02 | 0.1384705E-02 |

Encounter Frequency 1.5 Rads Per Sec

| | | |
|------------|---------------|---------------|
| Sea State: | 1 | 2 |
| K1= | 1.6945763 | 1.6945763 |
| T1= | 0.2571034 | 0.2571034 |
| T2= | 25.3036194 | 25.3036194 |
| T3= | 25.4920502 | 25.4920502 |
| T4= | 26.4106903 | 26.4106903 |
| Cost J= | 0.5423090E-04 | 0.6863636E-04 |

TABLE 6

Controller C For 60° Encounter Wave Angle

Encounter Frequency 0.2 Rads Per Sec

| | | |
|------------|---------------|---------------|
| Sea State: | 1 | 2 |
| K1= | 2.1659079 | 2.1752367 |
| T1= | 29.1530609 | 28.9752655 |
| T2= | 18.6070404 | 18.4342346 |
| T3= | 10.7567606 | 10.5662384 |
| T4= | 18.3101044 | 18.4618378 |
| Cost J= | 0.7797163E+00 | 0.9817770E+00 |

Encounter Frequency 0.4 Rads Per Sec

| | | |
|------------|---------------|---------------|
| Sea State: | 1 | 2 |
| K1= | 0.8408279 | 0.8623953 |
| T1= | 73.1355896 | 74.4368439 |
| T2= | 53.1565094 | 57.8289948 |
| T3= | 22.6398926 | 24.3586884 |
| T4= | 49.9999390 | 49.9900360 |
| Cost J= | 0.7811032E+00 | 0.9783571E+00 |

Encounter Frequency 0.6 Rads Per Sec

| | | |
|------------|---------------|---------------|
| Sea State: | 1 | 2 |
| K1= | 1.0592918 | 0.9676542 |
| T1= | 0.1000010 | 0.1343303 |
| T2= | 19.7355957 | 25.3748169 |
| T4= | 49.9999390 | 33.4176483 |
| Cost J= | 0.2017351E-02 | 0.2553086E-02 |

Encounter Frequency 0.75 Rads Per Sec

| | | |
|------------|---------------|---------------|
| Sea State: | 1 | 2 |
| K1= | 2.2673655 | 2.2673655 |
| T1= | 0.8431506 | 0.8431506 |
| T2= | 14.1734161 | 14.1734161 |
| T3= | 11.3151855 | 11.3151855 |
| T4= | 15.1259995 | 15.1259995 |
| Cost J= | 0.2704291E-02 | 0.3422481E-02 |

Encounter Frequency 1.5 Rads Per Sec

| | | |
|------------|---------------|---------------|
| Sea State: | 1 | 2 |
| K1= | 2.3734770 | 2.3808193 |
| T1= | 0.5810375 | 0.5764611 |
| T2= | 8.2907715 | 7.0220699 |
| T3= | 6.7814789 | 5.6438484 |
| T4= | 7.9672575 | 9.3380499 |
| Cost J= | 0.1145959E-02 | 0.1450353E-02 |

TABLE 7
Controller C For 90° Encounter Wave Angle

Encounter Frequency 0.2 Rads Per Sec

| | | |
|------------|---------------|---------------|
| Sea State: | 1 | 2 |
| K1= | 1.3473454 | 1.3487740 |
| T1= | 35.3837585 | 35.2085876 |
| T2= | 19.5286560 | 19.5352631 |
| T3= | 15.7849731 | 15.8424835 |
| T4= | 19.3971252 | 19.5299683 |
| Cost J= | 0.1756000E+01 | 0.2201721E+01 |

Encounter Frequency 0.4 Rads Per Sec

| | | |
|------------|---------------|---------------|
| Sea State: | 1 | 2 |
| K1= | 1.6298742 | 1.6293240 |
| T1= | 31.0220642 | 31.2911530 |
| T2= | 18.8860321 | 19.0679169 |
| T3= | 12.3363419 | 12.2226353 |
| T4= | 18.8753967 | 19.0280762 |
| Cost J= | 0.6726980E+00 | 0.8399093E+00 |

Encounter Frequency 0.6 Rads Per Sec

| | | |
|------------|---------------|---------------|
| Sea State: | 1 | 2 |
| K1= | 1.9138527 | 1.9098577 |
| T1= | 1.1895151 | 1.1946430 |
| T2= | 10.0705585 | 10.1293569 |
| T3= | 11.7410755 | 11.8040771 |
| T4= | 10.0737257 | 10.1994019 |
| Cost J= | 0.5086016E-01 | 0.6385970E-01 |

Encounter Frequency 0.75 Rads Per Sec

| | | |
|------------|---------------|---------------|
| Sea State: | 1 | 2 |
| K1= | 1.8993120 | 1.8893242 |
| T1= | 0.4503812 | 0.4850104 |
| T2= | 27.3063202 | 31.5392303 |
| T3= | 21.9325409 | 27.4768982 |
| T4= | 28.9246674 | 26.0999603 |
| Cost J= | 0.2837797E-01 | 0.3586013E-01 |

Encounter Frequency 1.5 Rads Per Sec

| | | |
|------------|---------------|---------------|
| Sea State: | 1 | 2 |
| K1= | 2.4287634 | 2.4257565 |
| T1= | 0.6342447 | 0.6373515 |
| T2= | 7.4652443 | 7.9898472 |
| T3= | 5.9140081 | 6.1980715 |
| T4= | 5.8591156 | 5.1957550 |
| Cost J= | 0.1057035E-01 | 0.1336560E-01 |

TABLE 8
Controller C For 0° Encounter Wave Angle

Encounter Frequency 0.2 Rads Per Sec

| | | | |
|------------|---------------|---------------|---------------|
| Sea State: | 4 | 6 | 7 |
| K1= | 1.39999996 | 1.39999996 | 1.39999996 |
| T1= | 58.22999957 | 58.22999957 | 58.22999957 |
| T2= | 24.00000000 | 24.00000000 | 24.00000000 |
| T3= | 10.50000000 | 10.50000000 | 10.50000000 |
| T4= | 3.00000000 | 3.00000000 | 3.00000000 |
| COST J= | 0.9972246E-33 | 0.3988896E-32 | 0.1221600E-31 |

Encounter Frequency 0.4 Rads Per Sec

| | | | |
|------------|---------------|---------------|---------------|
| Sea State: | 4 | 6 | 7 |
| K1= | 1.39999996 | 1.39999996 | 1.39999996 |
| T1= | 58.22999957 | 58.22999957 | 58.22999957 |
| T2= | 24.00000000 | 24.00000000 | 24.00000000 |
| T3= | 10.50000000 | 10.50000000 | 10.50000000 |
| T4= | 3.00000000 | 3.00000000 | 3.00000000 |
| COST J= | 0.1454213E-34 | 0.5816855E-34 | 0.1781412E-33 |

Encounter Frequency 0.6 Rads Per Sec

| | | | |
|------------|---------------|---------------|---------------|
| Sea State: | 4 | 6 | 7 |
| K1= | 1.39999996 | 1.39999996 | 1.39999996 |
| T1= | 58.22999957 | 58.22999957 | 58.22999957 |
| T2= | 24.00000000 | 24.00000000 | 24.00000000 |
| T3= | 10.50000000 | 10.50000000 | 10.50000000 |
| T4= | 3.00000000 | 3.00000000 | 3.00000000 |
| COST J= | 0.2919672E-36 | 0.1167868E-35 | 0.3576599E-35 |

Encounter Frequency 0.75 Rads Per Sec

| | | | |
|------------|---------------|---------------|---------------|
| Sea State: | 4 | 6 | 7 |
| K1= | 1.39999996 | 1.39999996 | 1.39999996 |
| T1= | 58.22999957 | 58.22999957 | 58.22999957 |
| T2= | 24.00000000 | 24.00000000 | 24.00000000 |
| T3= | 10.50000000 | 10.50000000 | 10.50000000 |
| T4= | 3.00000000 | 3.00000000 | 3.00000000 |
| COST J= | 0.2995968E-38 | 0.1198388E-37 | 0.3670063E-37 |

Encounter Frequency 1.5 Rads Per Sec

| | | | |
|------------|---------------|---------------|---------------|
| Sea State: | 4 | 6 | 7 |
| K1= | 1.39999996 | 1.39999996 | 1.39999996 |
| T1= | 58.22999957 | 58.22999957 | 58.22999957 |
| T2= | 24.00000000 | 24.00000000 | 24.00000000 |
| T3= | 10.50000000 | 10.50000000 | 10.50000000 |
| T4= | 3.00000000 | 3.00000000 | 3.00000000 |
| COST J= | 0.2307540E-38 | 0.9230160E-38 | 0.2826737E-37 |

TABLE 9
Controller C For 30° Encounter Wave Angle

Encounter Frequency 0.2 Rads Per Sec

| | | | |
|------------|---------------|---------------|---------------|
| Sea State: | 4 | 6 | 7 |
| K1= | 1.7466650 | 1.7746067 | 1.8194151 |
| T1= | 35.2978973 | 36.3333435 | 48.3066101 |
| T2= | 22.2485657 | 23.2952423 | 45.8587494 |
| T3= | 13.6511078 | 13.4007721 | 25.3368378 |
| T4= | 22.1172638 | 23.5081635 | 23.1087189 |
| COST J= | 0.9229971E+00 | 0.3496342E+01 | 0.9325538E+01 |

Encounter Frequency 0.4 Rads Per Sec

| | | | |
|------------|---------------|---------------|---------------|
| Sea State: | 4 | 6 | 7 |
| K1= | 0.2102537 | 0.2002187 | 0.2060161 |
| T1= | 92.8943787 | 99.9424896 | 95.9424133 |
| T2= | 23.9096680 | 24.3453674 | 24.2843170 |
| T3= | 39.9628601 | 39.9452667 | 38.9973450 |
| T4= | 33.1146698 | 33.9409027 | 33.4644012 |
| COST J= | 0.3595694E-02 | 0.1431070E-01 | 0.4376912E-01 |

Encounter Frequency 0.6 Rads Per Sec

| | | | |
|------------|---------------|---------------|---------------|
| Sea State: | 4 | 6 | 7 |
| K1= | 1.8260603 | 1.8175459 | 1.8287125 |
| T1= | 1.1601276 | 1.1572495 | 1.1652012 |
| T2= | 11.2977753 | 10.3958378 | 10.5659571 |
| T3= | 12.5801849 | 11.7078133 | 11.7124157 |
| T4= | 10.2739115 | 10.7313347 | 10.5683947 |
| COST J= | 0.2808505E-02 | 0.1122463E-01 | 0.3429835E-01 |

Encounter Frequency 0.75 Rads Per Sec

| | | | |
|------------|---------------|---------------|---------------|
| Sea State: | 4 | 6 | 7 |
| K1= | 2.2723074 | 2.3248615 | 2.3073282 |
| T1= | 0.8993683 | 0.8716087 | 0.8750648 |
| T2= | 22.2714996 | 13.4890442 | 13.0364380 |
| T3= | 20.4913177 | 10.3330994 | 10.1076660 |
| T4= | 10.0878286 | 12.5009842 | 13.1554108 |
| COST J= | 0.1709419E-02 | 0.6832119E-02 | 0.2090112E-01 |

Encounter Frequency 1.5 Rads Per Sec

| | | | |
|------------|---------------|---------------|---------------|
| Sea State: | 4 | 6 | 7 |
| K1= | 1.9173651 | 1.8726044 | 1.6678009 |
| T1= | 0.6582609 | 0.3396787 | 0.3818831 |
| T2= | 38.7910156 | 31.8340454 | 27.1428680 |
| T3= | 19.3868103 | 29.9999695 | 26.3686218 |
| T4= | 17.9940795 | 24.4667816 | 27.3681793 |
| COST J= | 0.8474453E-04 | 0.3389677E-03 | 0.1038366E-02 |

TABLE 10
Controller C For 60° Encounter Wave Angle

Encounter Frequency 0.2 Rads Per Sec

| | | | |
|------------|---------------|---------------|---------------|
| Sea State: | ⁴ | ⁶ | ⁷ |
| K1= | 2.1778851 | 2.2266541 | 2.2981157 |
| T1= | 29.6119080 | 31.9857025 | 35.2284546 |
| T2= | 18.7636871 | 19.4135590 | 24.2031403 |
| T3= | 10.2442350 | 7.8426695 | 8.8281393 |
| T4= | 18.3449402 | 19.8131866 | 24.7627716 |
| COST J= | 0.1205183E+01 | 0.4414552E+01 | 0.1080894E+02 |

Encounter Frequency 0.4 Rads Per Sec

| | | | |
|------------|---------------|---------------|---------------|
| Sea State: | ⁴ | ⁶ | ⁷ |
| K1= | 0.8723865 | 1.3212109 | 1.7475338 |
| T1= | 77.6901245 | 1.1219873 | 0.9073439 |
| T2= | 57.4288635 | 14.2327118 | 18.7083435 |
| T3= | 21.6142426 | 35.2742767 | 29.6310730 |
| T4= | 58.1057587 | 14.2909546 | 20.4921570 |
| COST J= | 0.1194492E+01 | 0.3620569E+01 | 0.1005195E+02 |

Encounter Frequency 0.6 Rads Per Sec

| | | | |
|------------|---------------|---------------|---------------|
| Sea State: | ⁴ | ⁶ | ⁷ |
| K1= | 0.9356804 | 1.0065041 | 0.9630518 |
| T1= | 0.2035089 | 0.1434612 | 0.1086842 |
| T2= | 25.2695007 | 28.2131348 | 24.0041809 |
| T3= | 18.3522491 | 16.1927643 | 17.7048645 |
| T4= | 39.1636200 | 29.4095917 | 38.1658936 |
| COST J= | 0.3151959E-02 | 0.1260864E-01 | 0.3862068E-01 |

Encounter Frequency 0.75 Rads Per Sec

| | | | |
|------------|---------------|---------------|---------------|
| Sea State: | ⁴ | ⁶ | ⁷ |
| K1= | 2.2310591 | 2.2579184 | 2.2688522 |
| T1= | 0.8066239 | 0.7918448 | 0.7898693 |
| T2= | 18.4929504 | 14.8840103 | 14.6062164 |
| T3= | 16.4596100 | 12.1710510 | 11.3906097 |
| T4= | 12.6112747 | 14.9709930 | 14.7650146 |
| COST J= | 0.4225172E-02 | 0.1688830E-01 | 0.5162057E-01 |

Encounter Frequency 1.5 Rads Per Sec

| | | | |
|------------|---------------|---------------|---------------|
| Sea State: | ⁴ | ⁶ | ⁷ |
| K1= | 2.3292980 | 2.3723307 | 2.3858051 |
| T1= | 0.5873335 | 0.5848479 | 0.6092799 |
| T2= | 21.2806244 | 8.7543087 | 8.3835888 |
| T3= | 20.8198700 | 7.1684380 | 6.6424551 |
| T4= | 5.3823652 | 7.0838490 | 7.5094414 |
| COST J= | 0.1791609E-02 | 0.7157017E-02 | 0.2188155E-01 |

TABLE 11
Controller C For 90° Encounter Wave Angle

Encounter Frequency 0.2 Rads Per Sec

| | | | |
|------------|---------------|---------------|---------------|
| Sea State: | 4 | 6 | 7 |
| K1= | 1.3517475 | 1.3857212 | 1.4623213 |
| T1= | 35.3476257 | 36.2312164 | 42.9548187 |
| T2= | 19.6020966 | 21.4780426 | 28.4767914 |
| T3= | 15.6134491 | 15.0542984 | 14.1265106 |
| T4= | 19.6564178 | 21.3916779 | 28.5155182 |
| COST J= | 0.2690107E+01 | 0.9237458E+01 | 0.2028659E+02 |

Encounter Frequency 0.4 Rads Per Sec

| | | | |
|------------|---------------|---------------|---------------|
| Sea State: | 4 | 6 | 7 |
| K1= | 1.0069885 | 1.1330795 | 1.1926146 |
| T1= | 49.7900391 | 3.6114454 | 0.7214398 |
| T2= | 36.0238495 | 18.1521301 | 37.0983887 |
| T3= | 15.7164612 | 31.1608582 | 39.9669037 |
| T4= | 35.5061340 | 17.9342651 | 38.7577972 |
| COST J= | 0.8278778E+01 | 0.1712465E+02 | 0.2298665E+02 |

Encounter Frequency 0.6 Rads Per Sec

| | | | |
|------------|---------------|---------------|---------------|
| Sea state: | 4 | 6 | 7 |
| K1= | 1.8570919 | 1.9276266 | 1.8934374 |
| T1= | 1.0337286 | 0.9287271 | 0.4949190 |
| T2= | 11.9529600 | 15.0574036 | 30.3212738 |
| T3= | 12.3197098 | 13.4190674 | 27.2785339 |
| T4= | 11.7377634 | 15.0851593 | 26.5594635 |
| COST J= | 0.9655529E-01 | 0.2932869E+00 | 0.5224001E+00 |

Encounter Frequency 0.75 Rads Per Sec

| | | | |
|------------|---------------|---------------|---------------|
| Sea state: | 4 | 6 | 7 |
| K1= | 1.9137421 | 1.8589468 | 1.7544203 |
| T1= | 0.4686716 | 0.3916095 | 0.1022463 |
| T2= | 26.6723328 | 32.9264069 | 42.4169006 |
| T3= | 20.3362122 | 27.4372711 | 29.9568634 |
| T4= | 30.0011749 | 32.4602356 | 52.5700073 |
| COST J= | 0.4419509E-01 | 0.1722615E+00 | 0.4958326E+00 |

Encounter Frequency 1.5 Rads Per Sec

| | | | |
|------------|---------------|---------------|---------------|
| Sea State: | 4 | 6 | 7 |
| K1= | 2.3951197 | 2.4414005 | 2.4639597 |
| T1= | 0.6277218 | 0.6339726 | 0.6183524 |
| T2= | 4.0210686 | 6.7097816 | 7.3951139 |
| T3= | 6.0798759 | 4.9043417 | 5.1939421 |
| T4= | 69.4311066 | 6.7554045 | 7.3074417 |
| COST J= | 0.1650761E-01 | 0.6472868E-01 | 0.1906425E+00 |

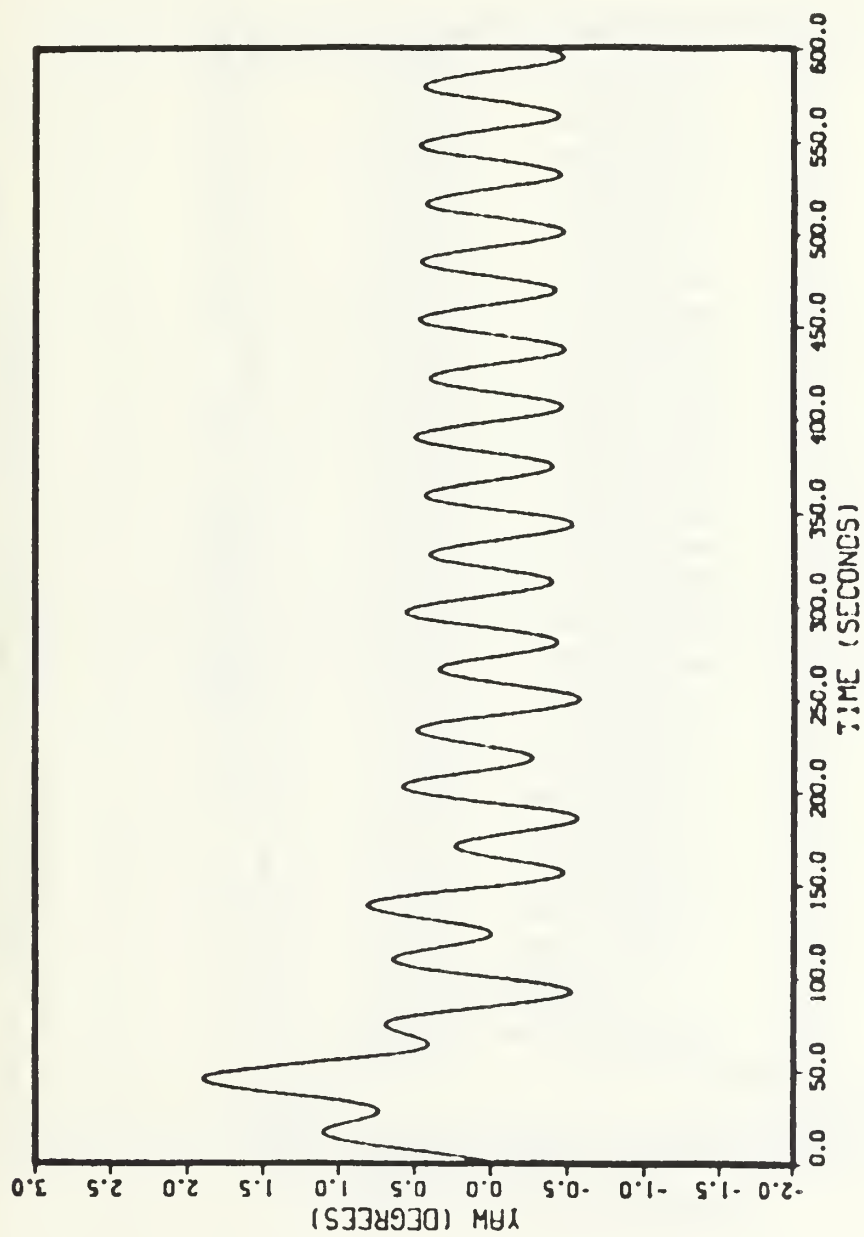


Figure 4.2 Yaw Vs Time, Sea State 4.
Encounter Frequency 0.2 rads per sec, Encounter Angle 30°

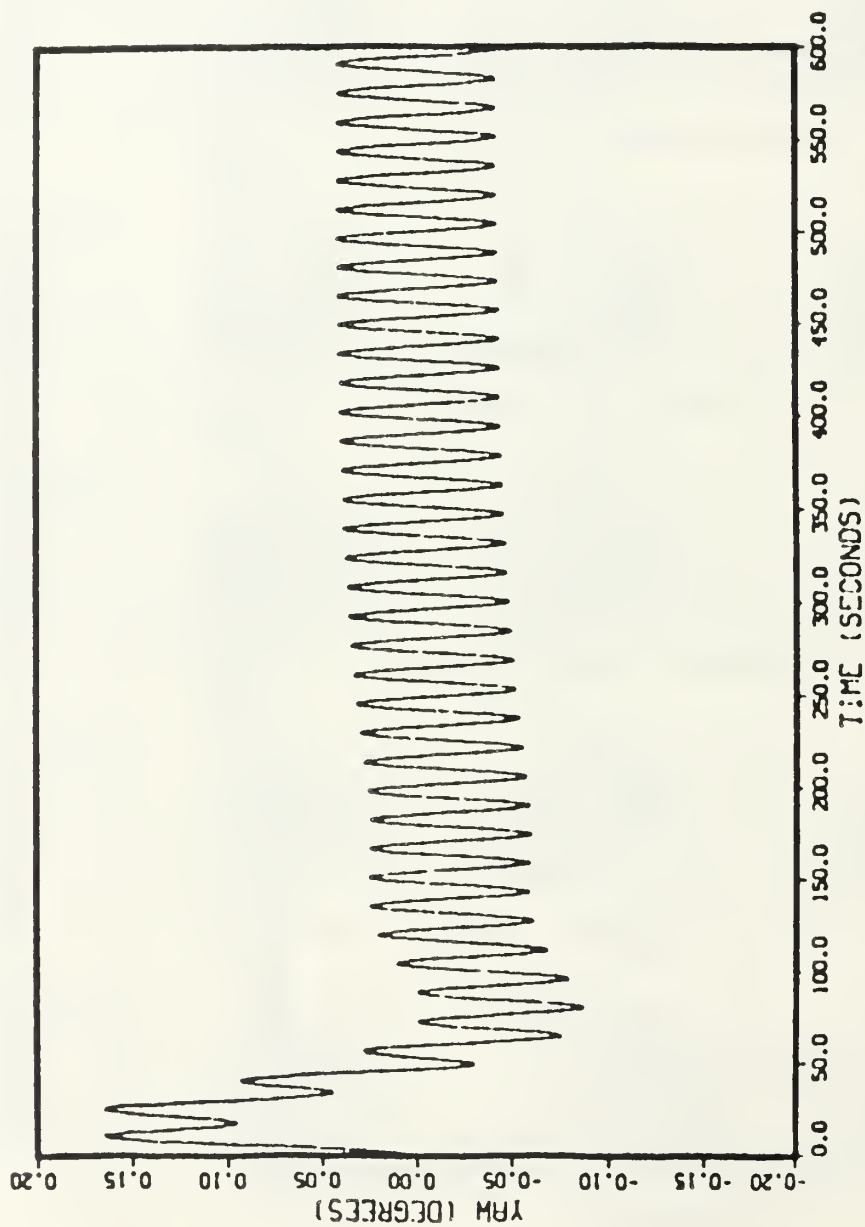


Figure 4.3 Yaw Vs Time, Sea State 4.
Encounter Frequency 0.4 rads per sec, Encounter Angle 30°

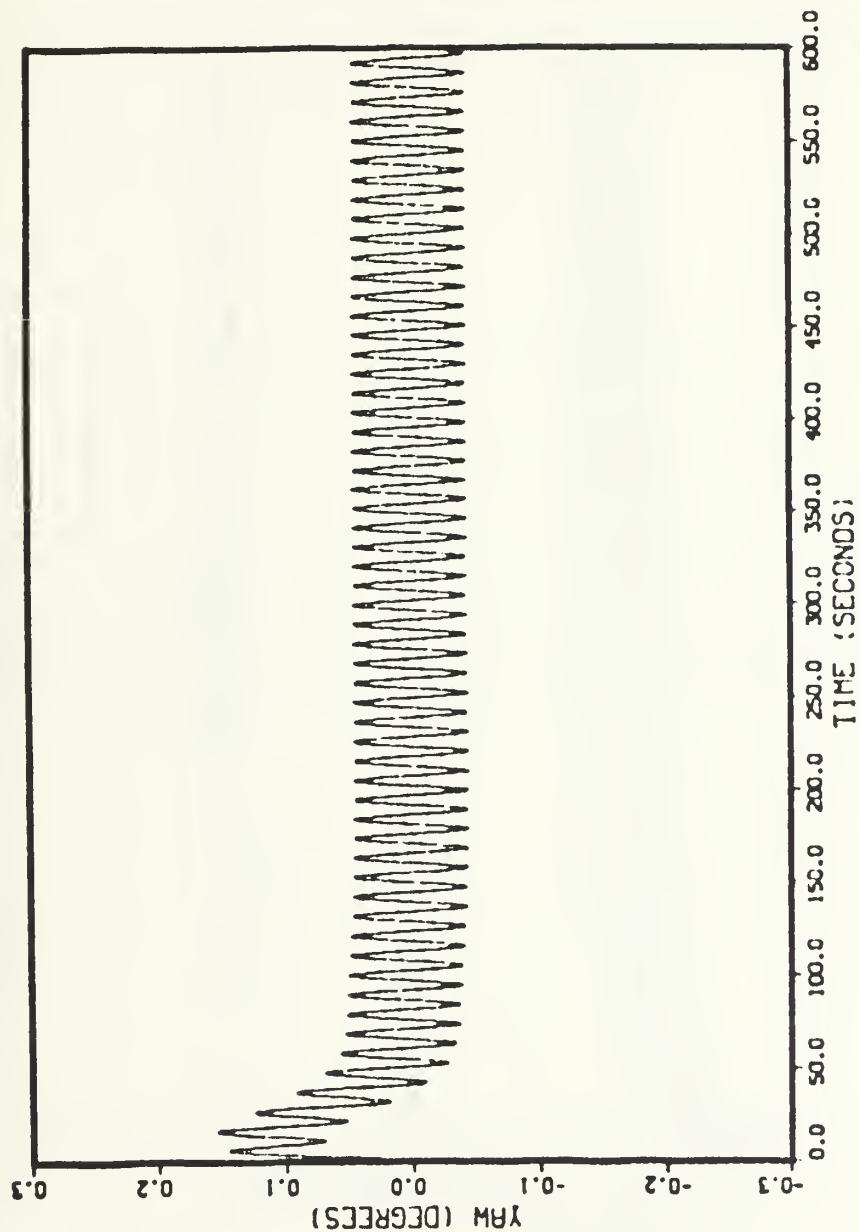


Figure 4.4 Yaw Vs Time, Sea State 4.
Encounter Frequency 0.6 rads per sec, Encounter Angle 30°

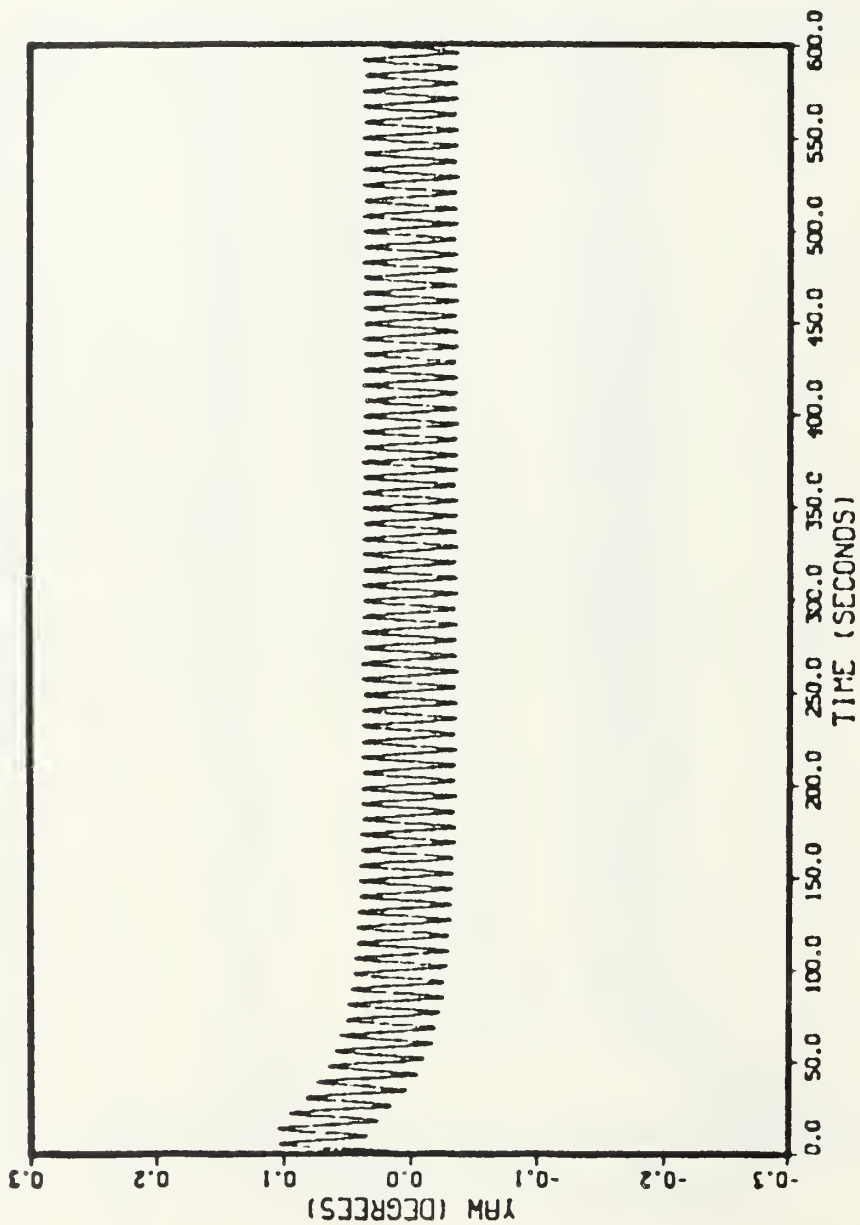


Figure 4.5 Yaw Vs Time, Sea State 4.
Encounter Frequency 0.75 rads per sec, Encounter Angle 30°

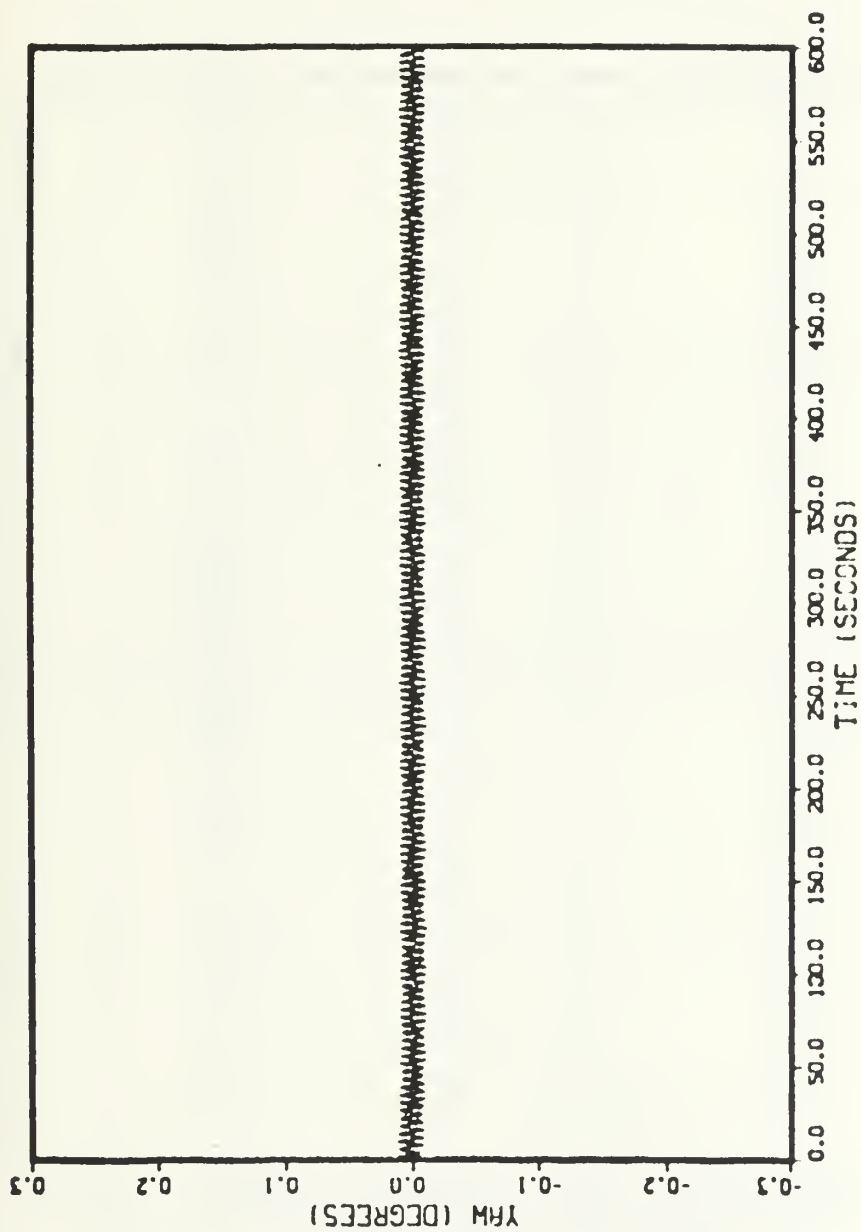


Figure 4.6 Yaw Vs Time, Sea State 4.
Encounter Frequency 1.5 rads per sec, Encounter Angle 30°

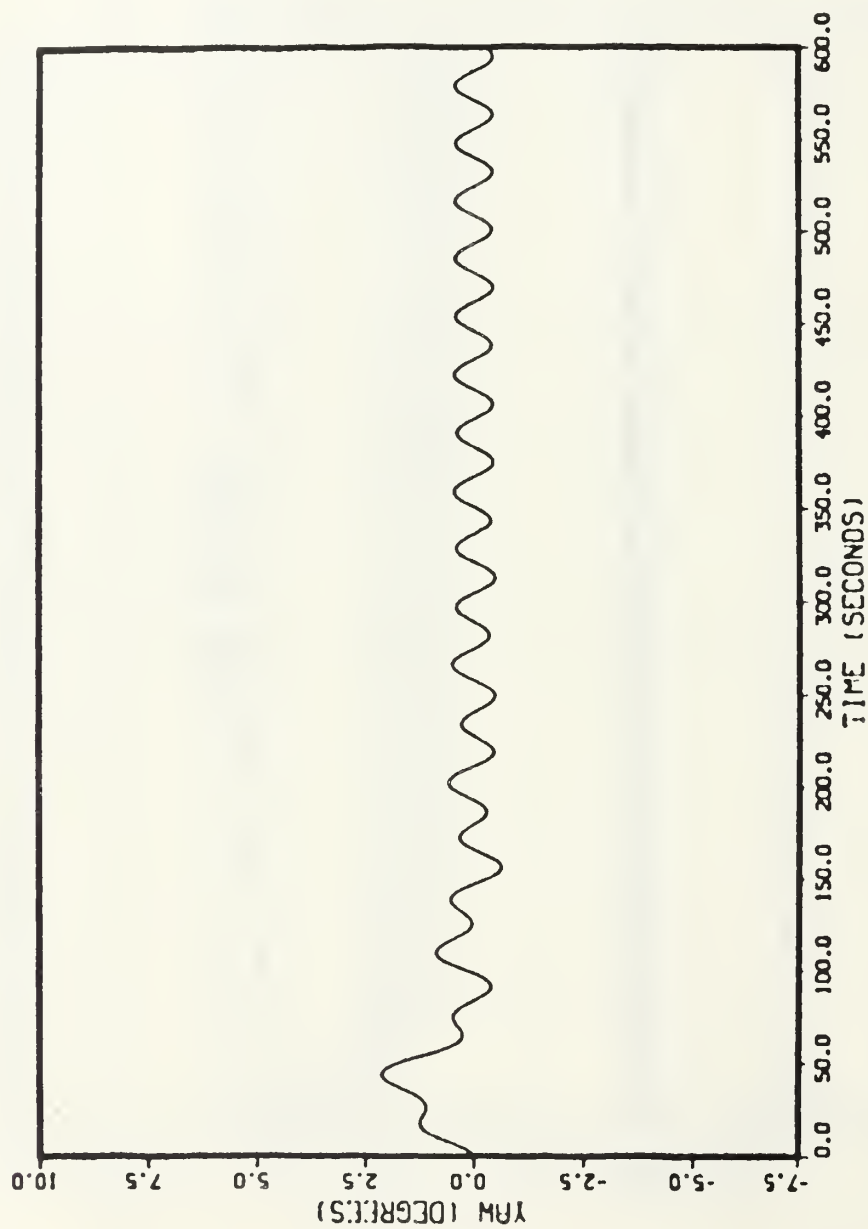


Figure 4.7 Yaw Vs Time, Sea State 4.
Encounter Frequency 0.2 rads per sec, Encounter Angle 60°

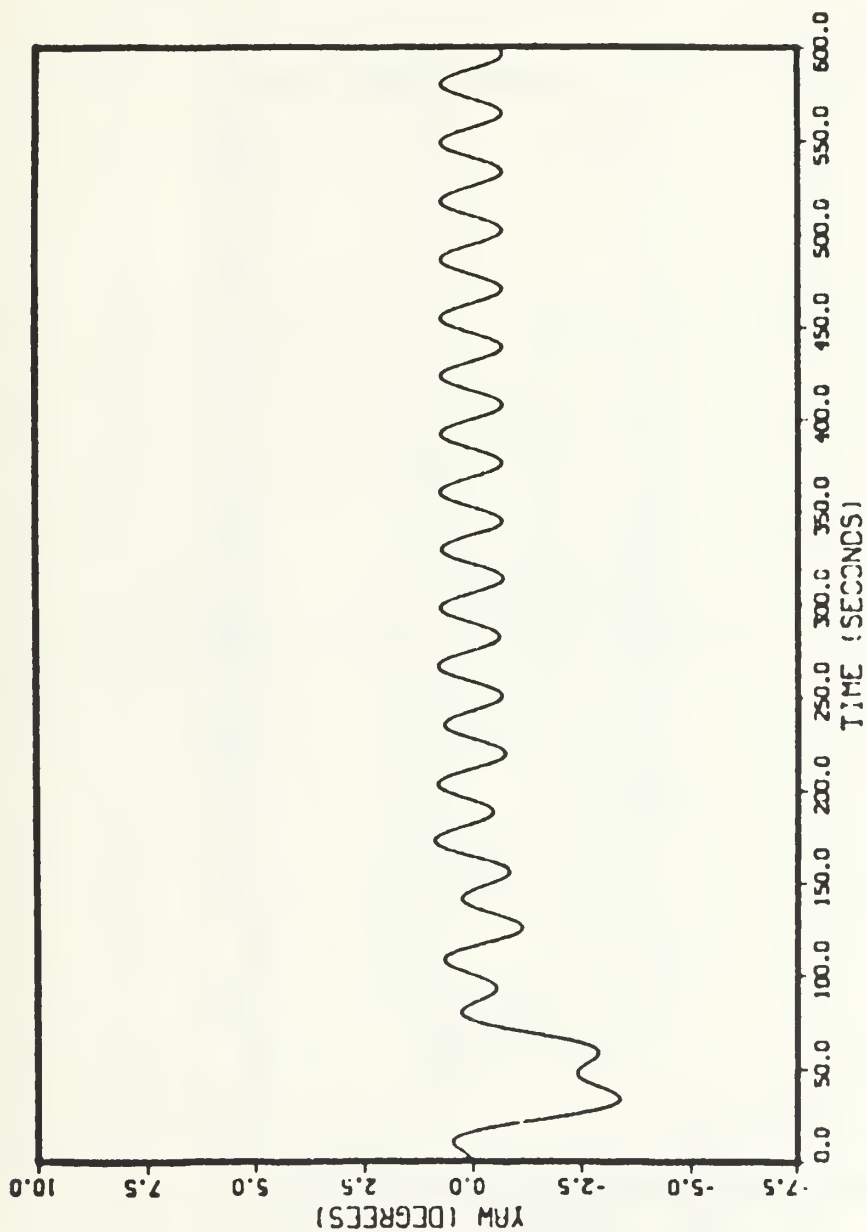


Figure 4.8 Yaw Vs Time, Sea State 4.
Encounter Frequency 0.2 rads per sec, Encounter Angle 90°

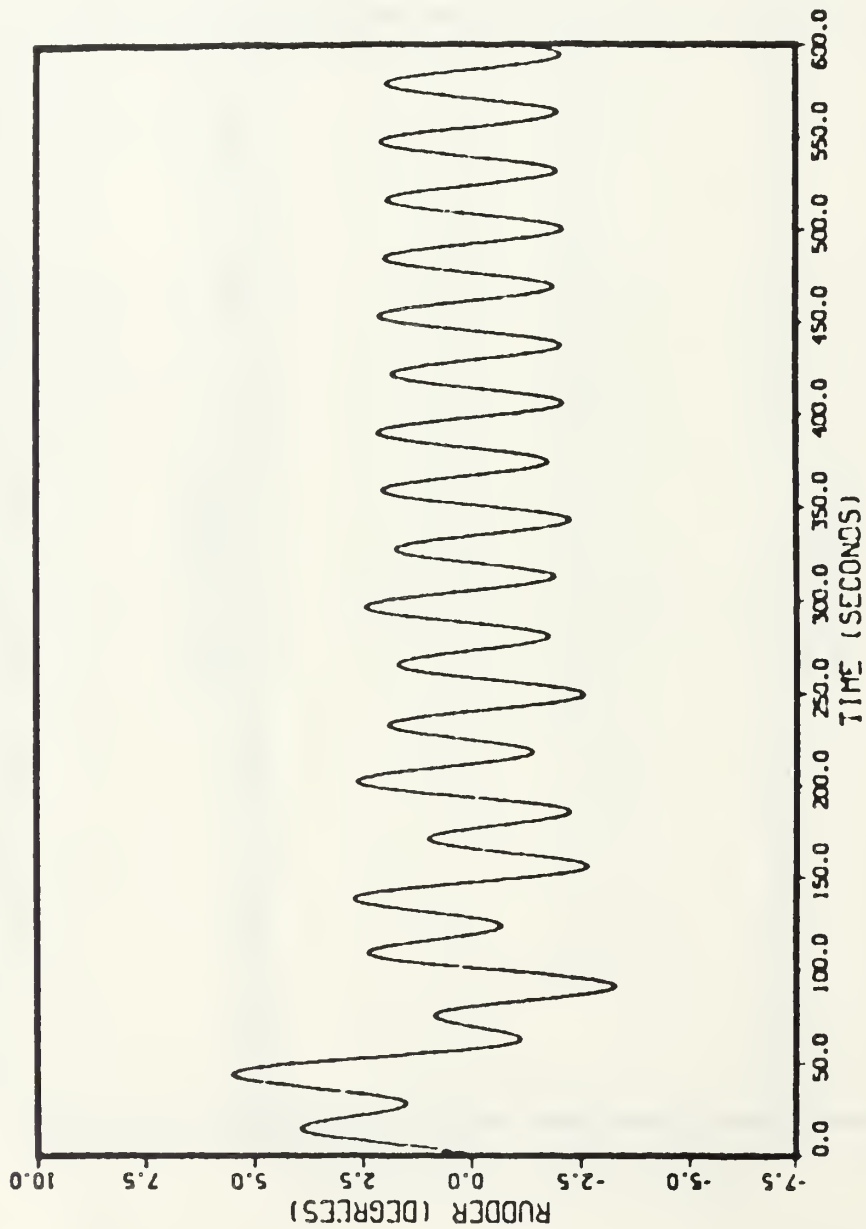


Figure 4.9 Rudder Vs Time, Sea State 4.
Encounter Frequency 0.2 rads per sec, Encounter Angle 30°

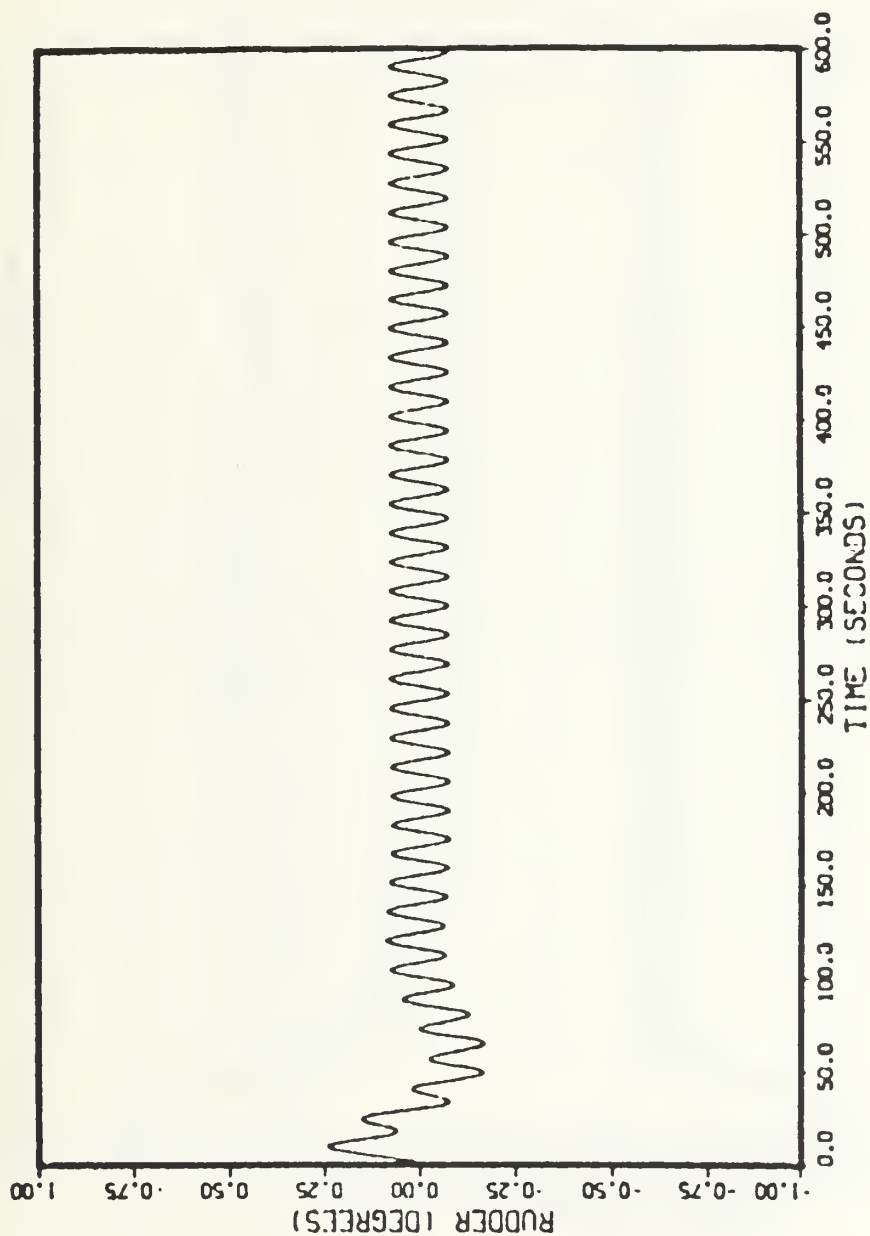


Figure 4.10 Rudder Vs Time, Sea State 4.
Encounter Frequency 0.4 rads per sec, Encounter Angle 30°

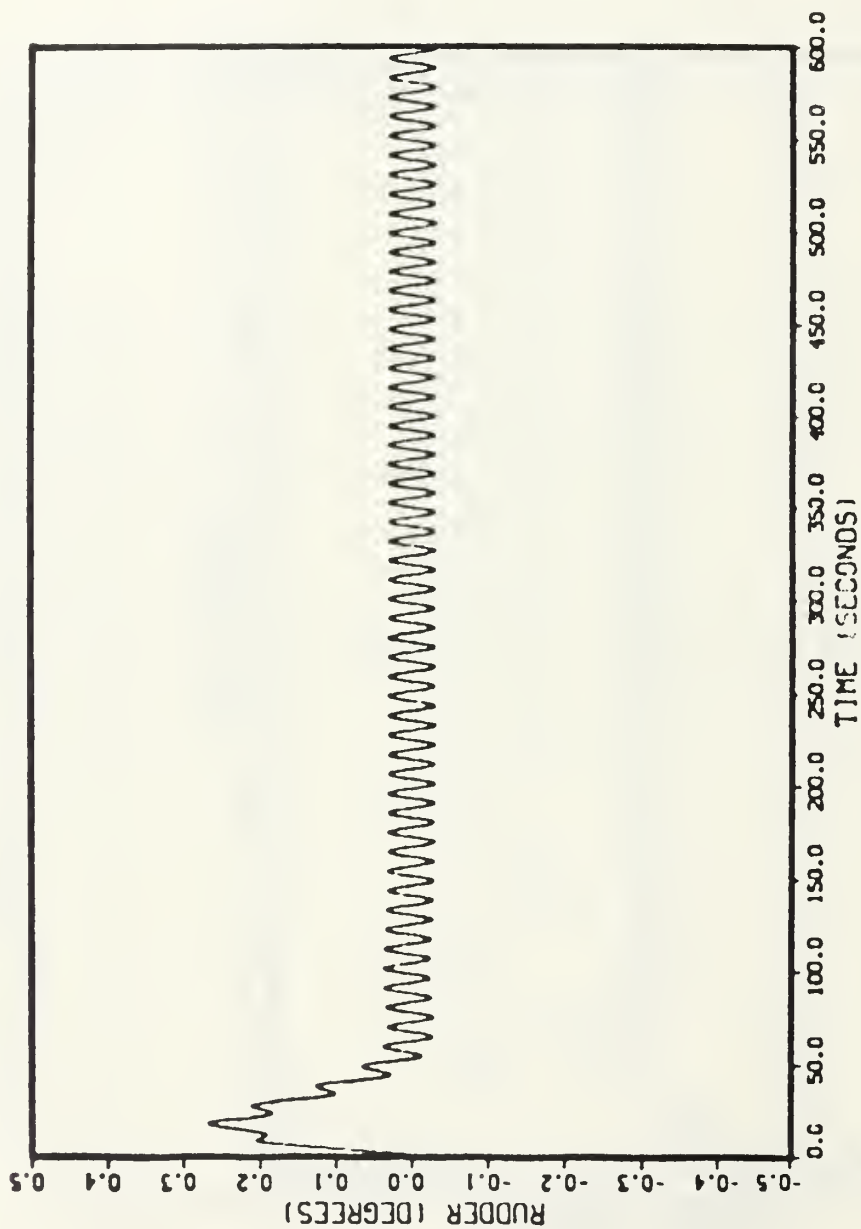


Figure 4.11 Rudder Vs Time, Sea State 4,
Encounter Frequency 0.6 rads per sec, Encounter Angle 30°

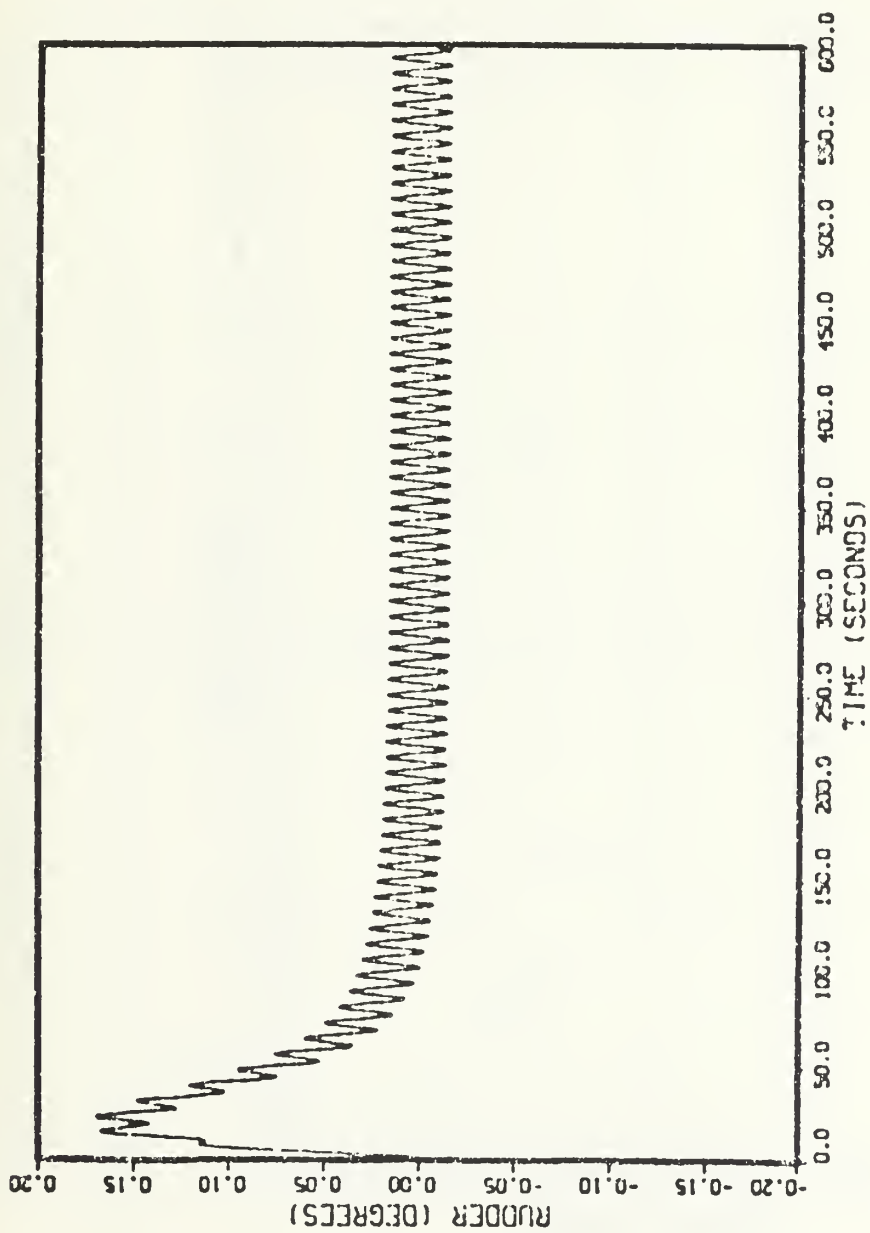


Figure 4.12 Rudder Vs Time, Sea State 4.
Encounter Frequency 0.75 rads per sec, Encounter Angle 30°

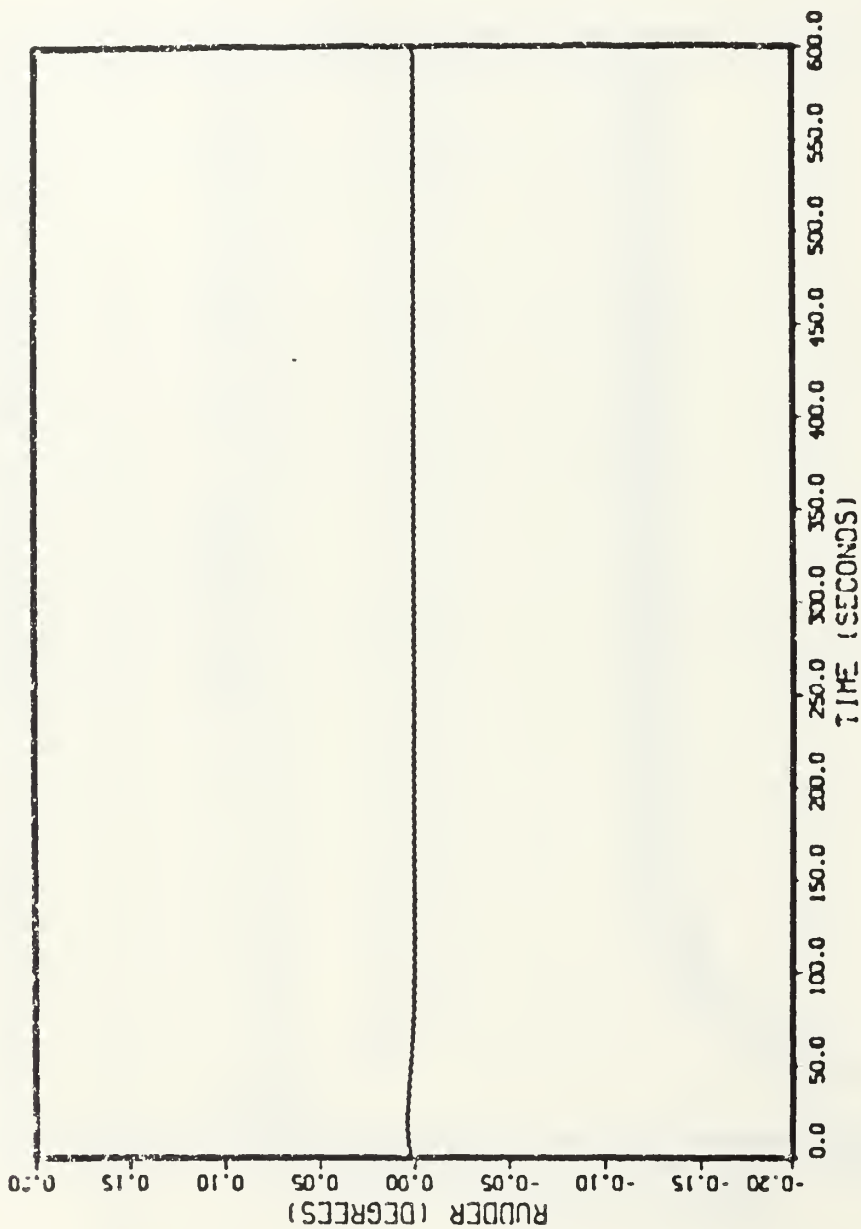


Figure 4.13 Rudder Vs Time, Sea State 4,
Encounter Frequency 1.5 rads per sec, Encounter Angle 30°

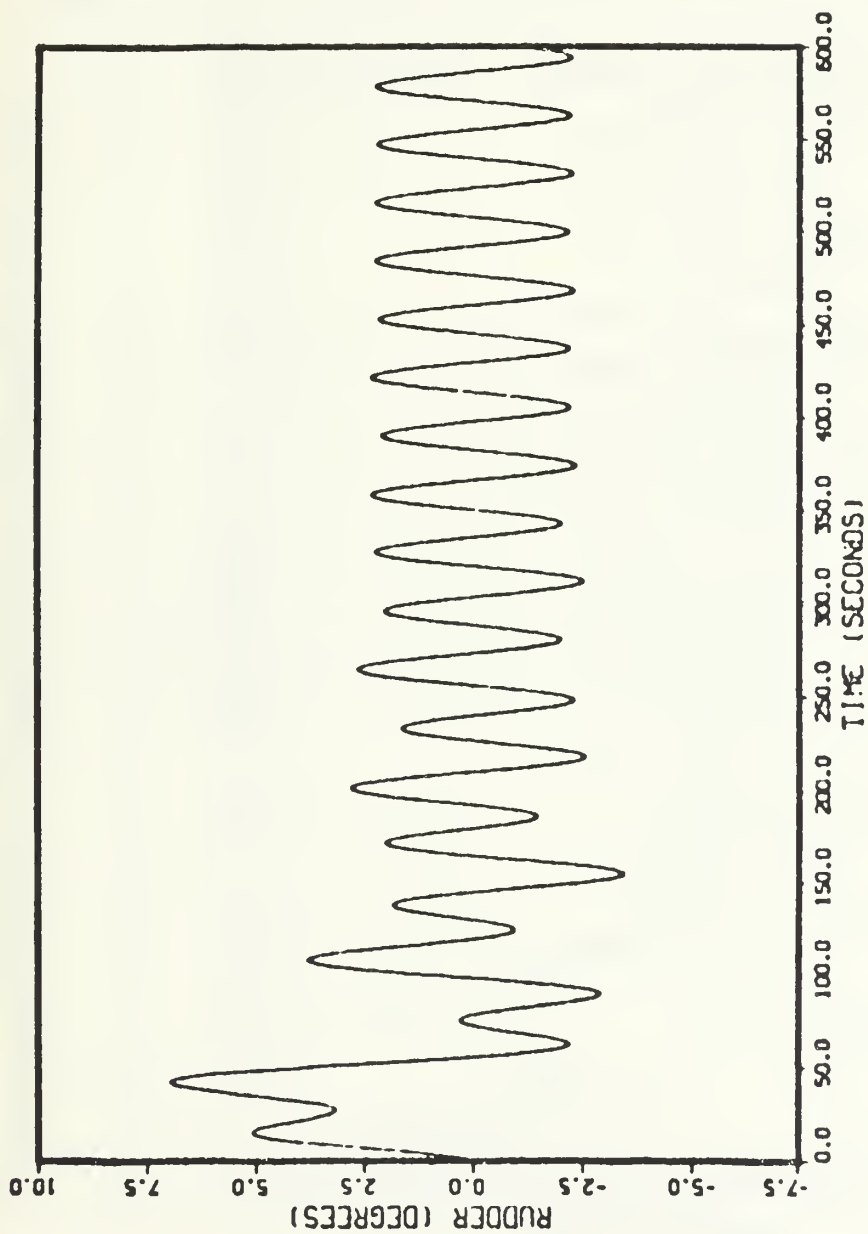


Figure 4.14 Rudder Vs Time, Sea State 4,
Encounter Frequency 0.2 rads per sec, Encounter Angle 60°

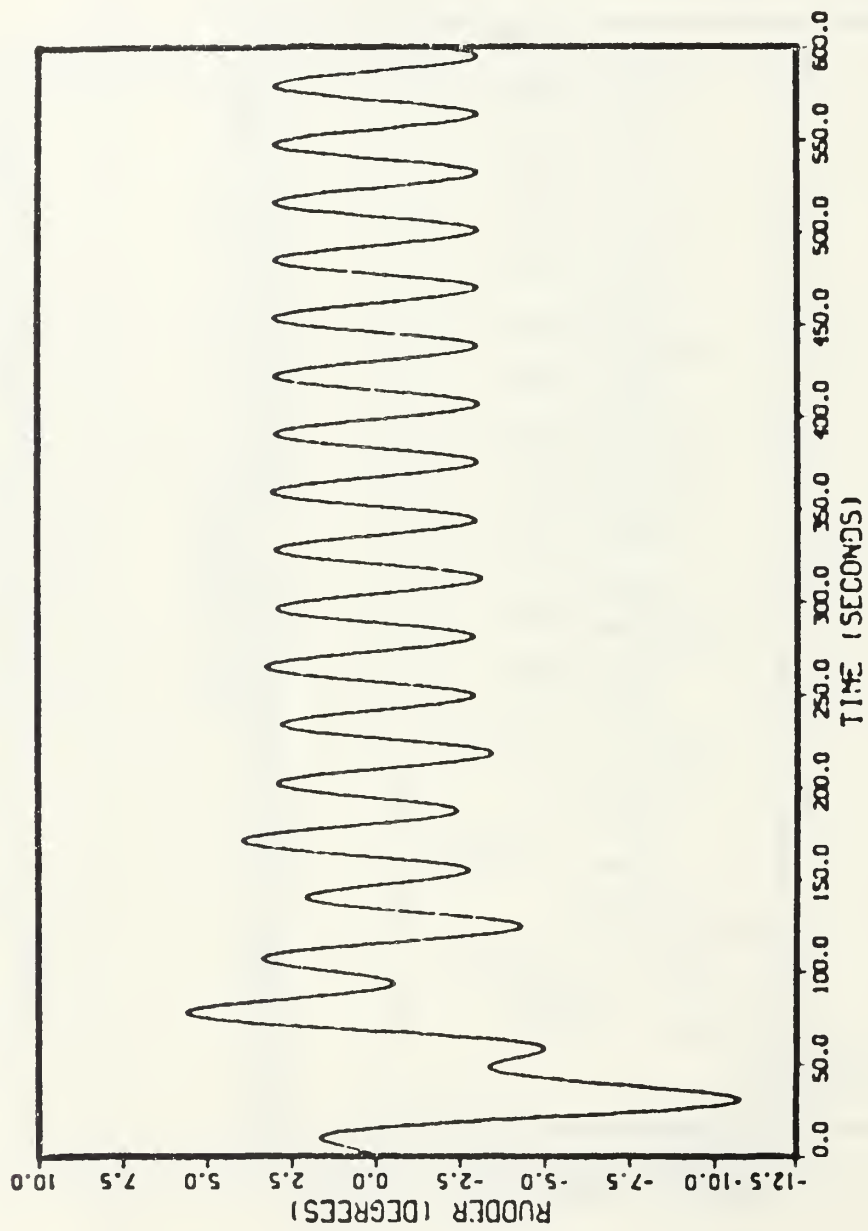


Figure 4.15 Rudder Vs Time, Sea State 4.
Encounter Frequency 0.2 rads per sec, Encounter Angle 90°

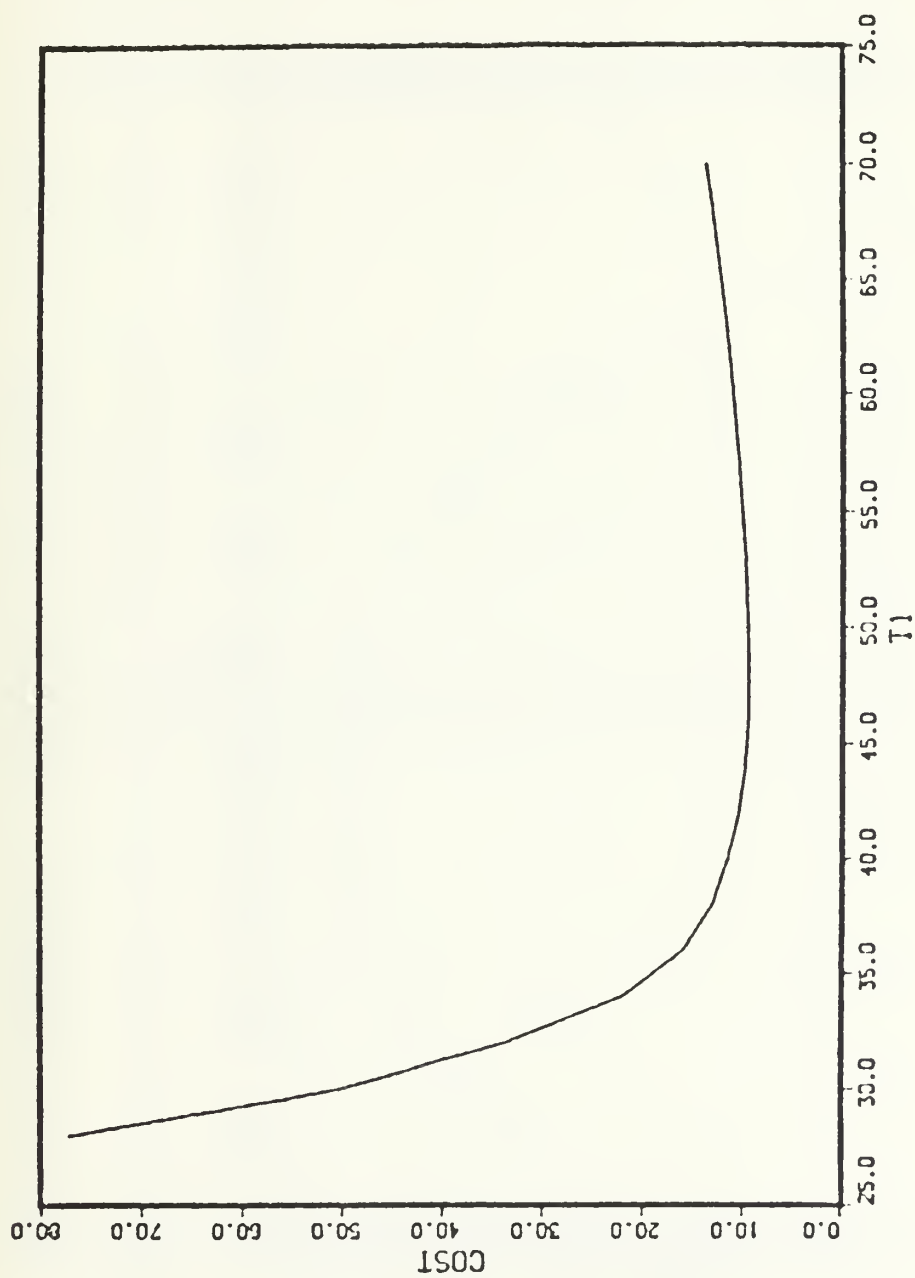


Figure 4.16. Cost Vs T1, Sea State 7.
Encounter Frequency 0.2 rads per sec, Encounter Angle 30°

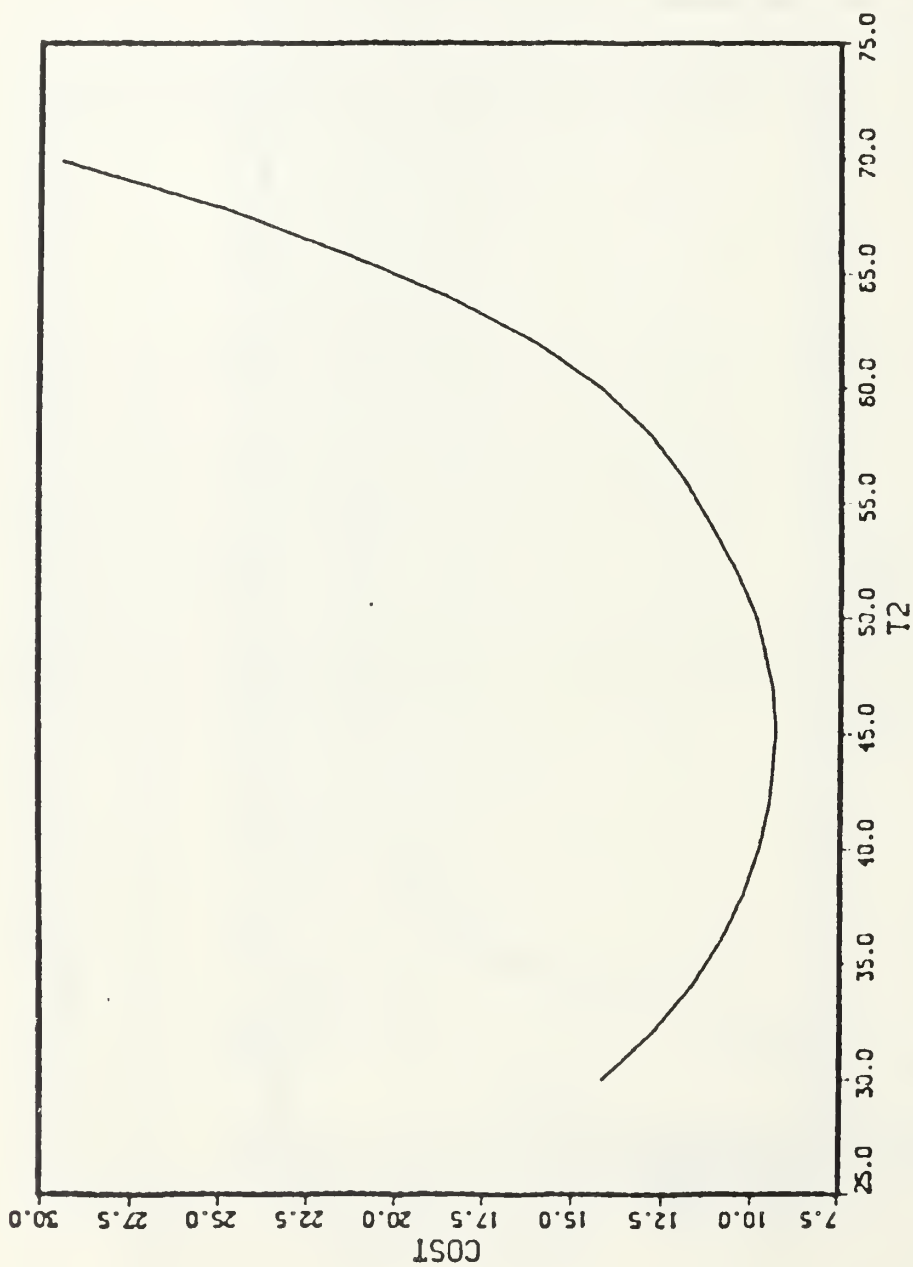


Figure 4.17 Cost Vs T2, Sea State 7.
Encounter Frequency 0.2 rads per sec, Encounter Angle 30°

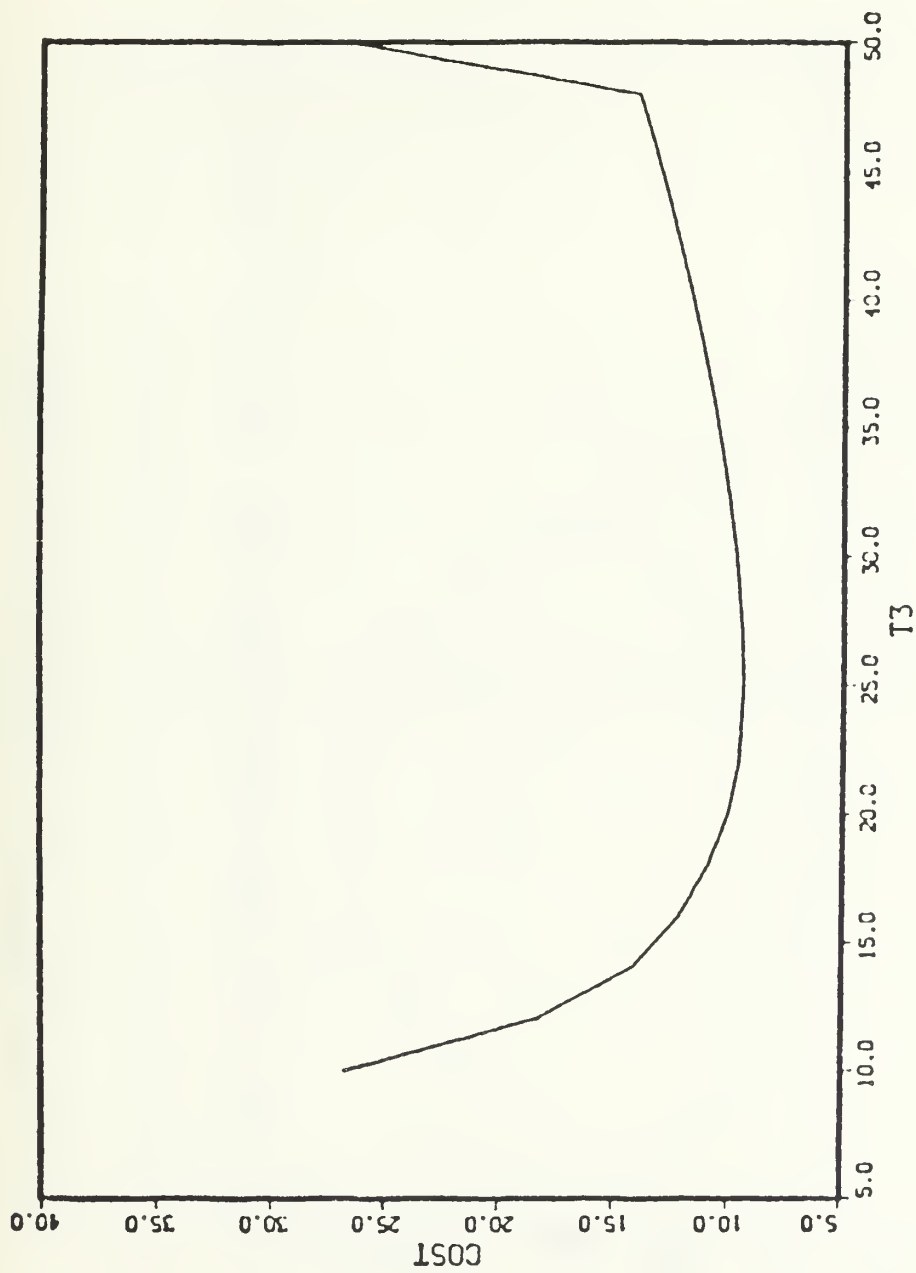


Figure 4.18 Cost Vs T3, Sea State 7.
Encounter Frequency 0.2 rads per sec, Encounter Angle 30°

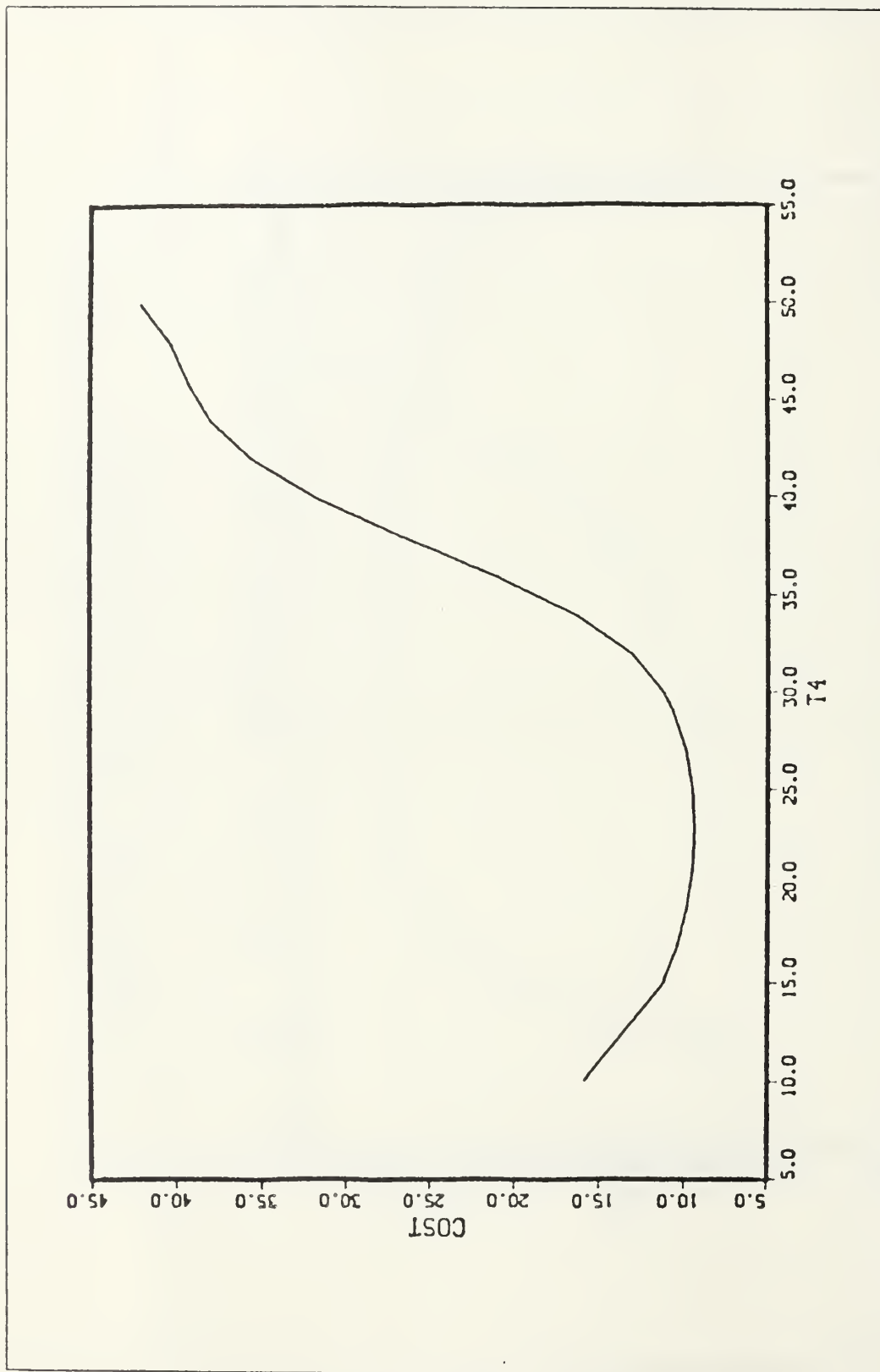


Figure 4.19 Cost Vs T4, Sea State 7.
Encounter Frequency 0.2 rads per sec, Encounter Angle 30°

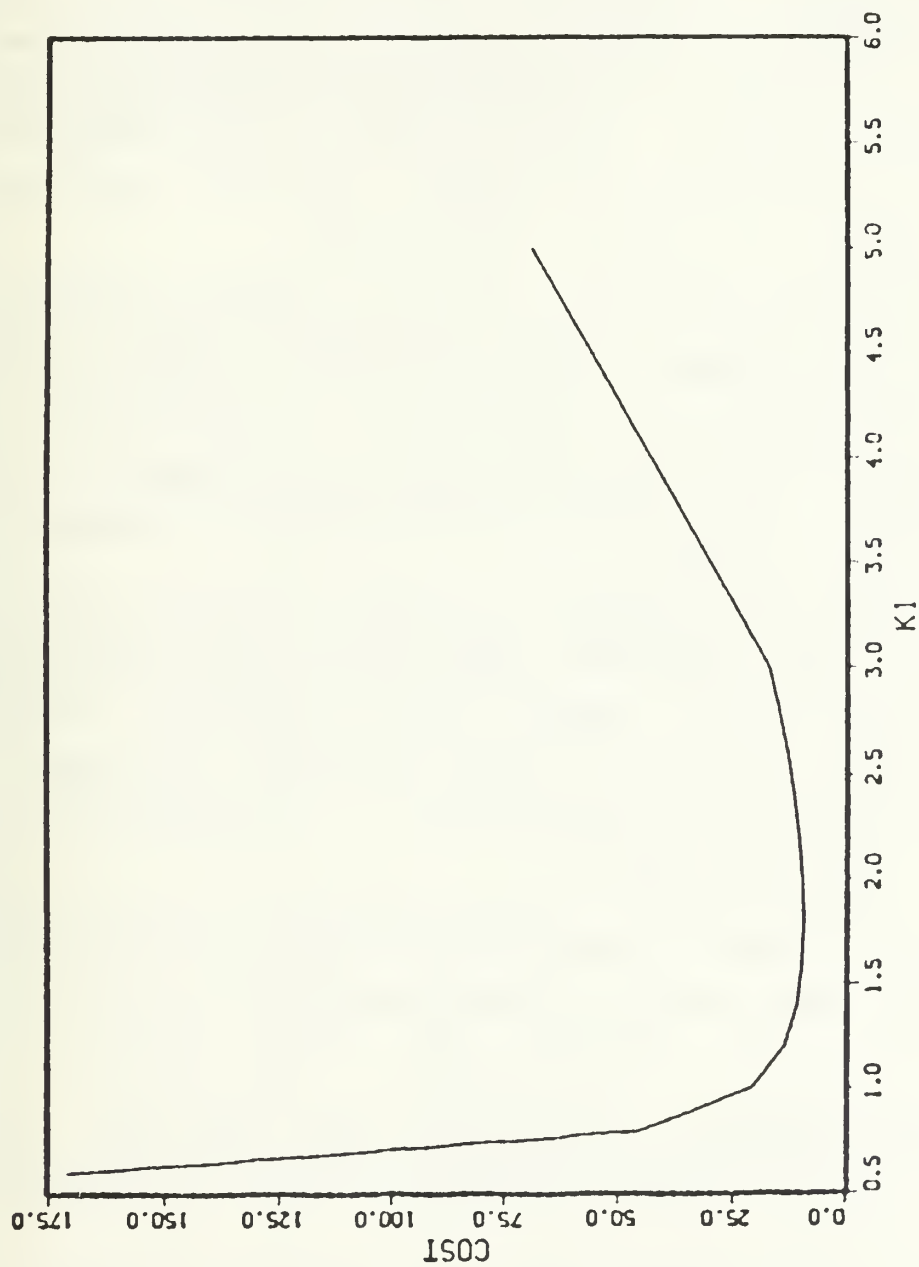


Figure 4.20 Cost Vs K_1 , Sea State 7.
Encounter Frequency 0.2 rads per sec, Encounter Angle 30°

V. IRREGULAR SEAS-CONTROLLER DESIGN

A sea state generator program which generates added mass, added inertia values and in addition calculates the forces and moments, was coupled to the fortran program shown in Appendix D, so that the function minimization subroutine (BOXPLX) could be used in the presence of the irregular sea. The forces and moments were stored in a look up table which was coupled to the equation of motion.

The optimal gains obtained for 0.75 rad/sec encounter frequency in the regular sea study were used as the initial guess in order to evaluate the optimal controller parameters involving the irregular sea.

It is known that sea is never regular but actually is a random phenomenon where waves are continually changing in height, length and breadth.

Since the sea state during this study is represented by irregular waves then the waves impinging on the ship hull would contain the total energy density spectrum. This density spectrum is composed of many frequencies and therefore the response of the ship would be to an average value of added mass and added inertia.

For this study where the ship's speed is 23 knots, the controller has the form of equation B.1, we used values for added mass and added inertia corresponding to 0.75 rad/sec because close to that frequency the energy density is maximum.

The optimal controller parameters found are shown in Table 12, and typical system's response is shown in Figures 5.1, 5.2, 5.3, 5.4, 5.5

These plots were obtained using the program of Appendix E.

A careful analysis of the extracted results leads to conclude:

- The maximum deviation of controller parameters values occurred at 30° encounter angle.
- For all encounter angles the maximum cost occurred for sea state 7.
- For specific encounter angles the higher the sea state the higher the cost.

TABLE 12

Controller C for Different Encounter Wave Angle

0° Encounter Wave Angle

Encounter Frequency 0.75 Rads Per Sec

| | | | |
|------------|---------------|---------------|---------------|
| Sea State: | 4 | 6 | 7 |
| K1= | 1.7460003 | 1.7460003 | 1.7460003 |
| T1= | 35.2969971 | 35.2969971 | 35.2969971 |
| T2= | 22.2480011 | 22.2480011 | 22.2480011 |
| T3= | 13.6510000 | 13.6510000 | 13.6510000 |
| T4= | 22.1170044 | 22.1170044 | 22.1170044 |
| Cost J= | 0.9438775E-34 | 0.3782326E-34 | 0.4605412E-33 |

30° Encounter Wave Angle

Encounter Frequency 0.75 Rads Per Sec

| | | | |
|------------|---------------|---------------|---------------|
| Sea State: | 4 | 6 | 7 |
| K1= | 2.4596768 | 1.5688477 | 2.4804857 |
| T1= | 88.2797241 | 47.3260040 | 56.3383179 |
| T2= | 50.5678864 | 35.6789203 | 51.4950714 |
| T3= | 5.2703905 | 21.5429993 | 5.7071409 |
| T4= | 95.3189392 | 25.0237122 | 91.6153102 |
| Cost J= | 0.8905333E-01 | 0.4461777E-01 | 0.1304857E+00 |

60° Encounter Wave Angle

Encounter Frequency 0.75 Rads Per Sec

| | | | |
|------------|---------------|---------------|---------------|
| Sea State: | 4 | 6 | 7 |
| K1= | 0.3419376 | 0.1919854 | 0.2646747 |
| T1= | 99.6322021 | 16.3320312 | 15.4308896 |
| T2= | 35.0456085 | 38.0289001 | 35.0908203 |
| T3= | 38.9945677 | 34.9145813 | 38.4357300 |
| T4= | 25.1149750 | 60.8223572 | 62.9836578 |
| Cost J= | 0.1788034E-03 | 0.3666982E-02 | 0.1193313E-01 |

90° Encounter Wave Angle

Encounter Frequency 0.75 Rads Per Sec

| | | | |
|------------|---------------|---------------|---------------|
| Sea State: | 4 | 6 | 7 |
| K1= | 0.5902819 | 2.4912267 | 2.4547853 |
| T1= | 87.4059400 | 55.7961656 | 32.7171021 |
| T2= | 34.5666444 | 35.6789999 | 33.8865433 |
| T3= | 39.6794654 | 30.2094433 | 4.9768888 |
| T4= | 25.1668799 | 25.0789005 | 25.3325553 |
| Cost J= | 0.7864684E-01 | 0.1778146E-01 | 0.2522047E+00 |

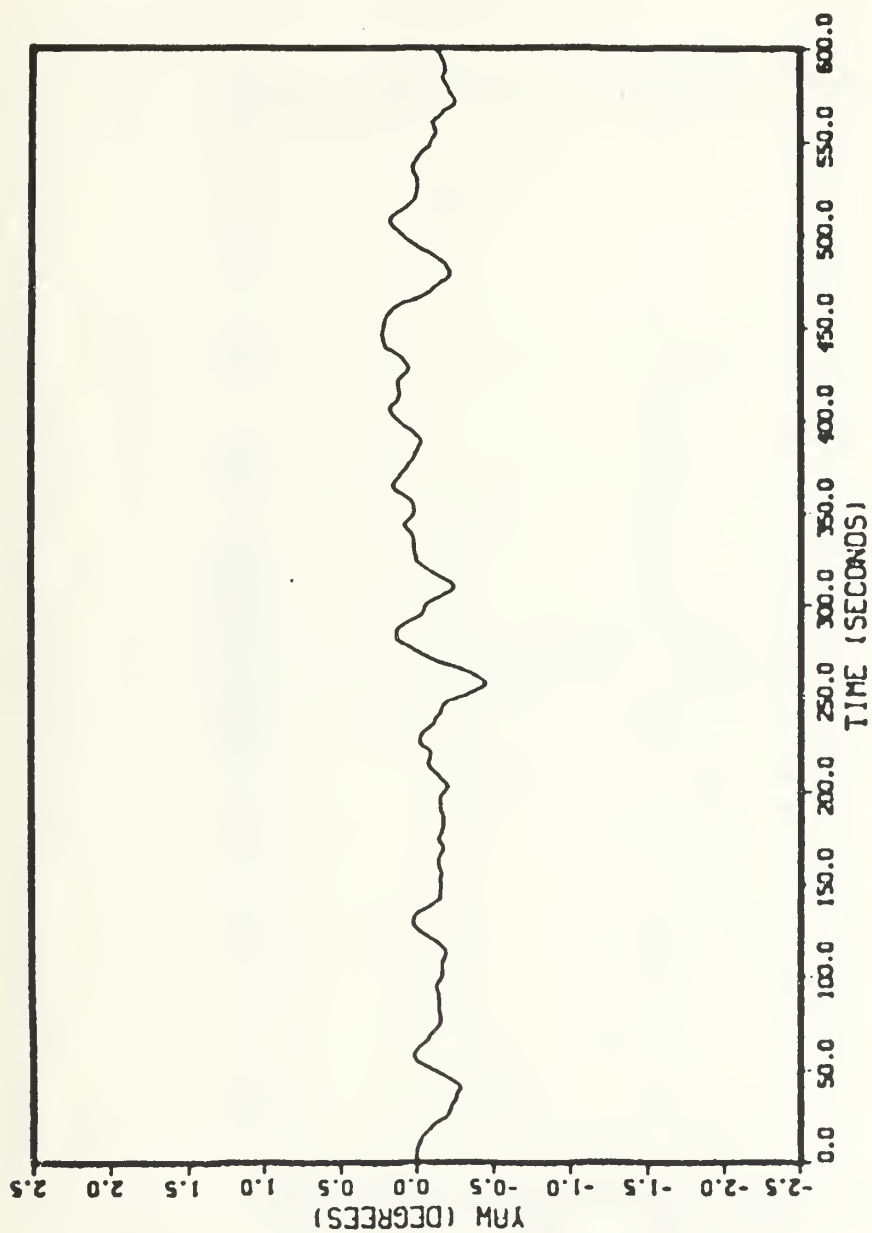


Figure 5.1 Yaw vs Time, Sea State 4.
Encounter Frequency 0.75 Rads Per Sec, Encounter Angle 30°

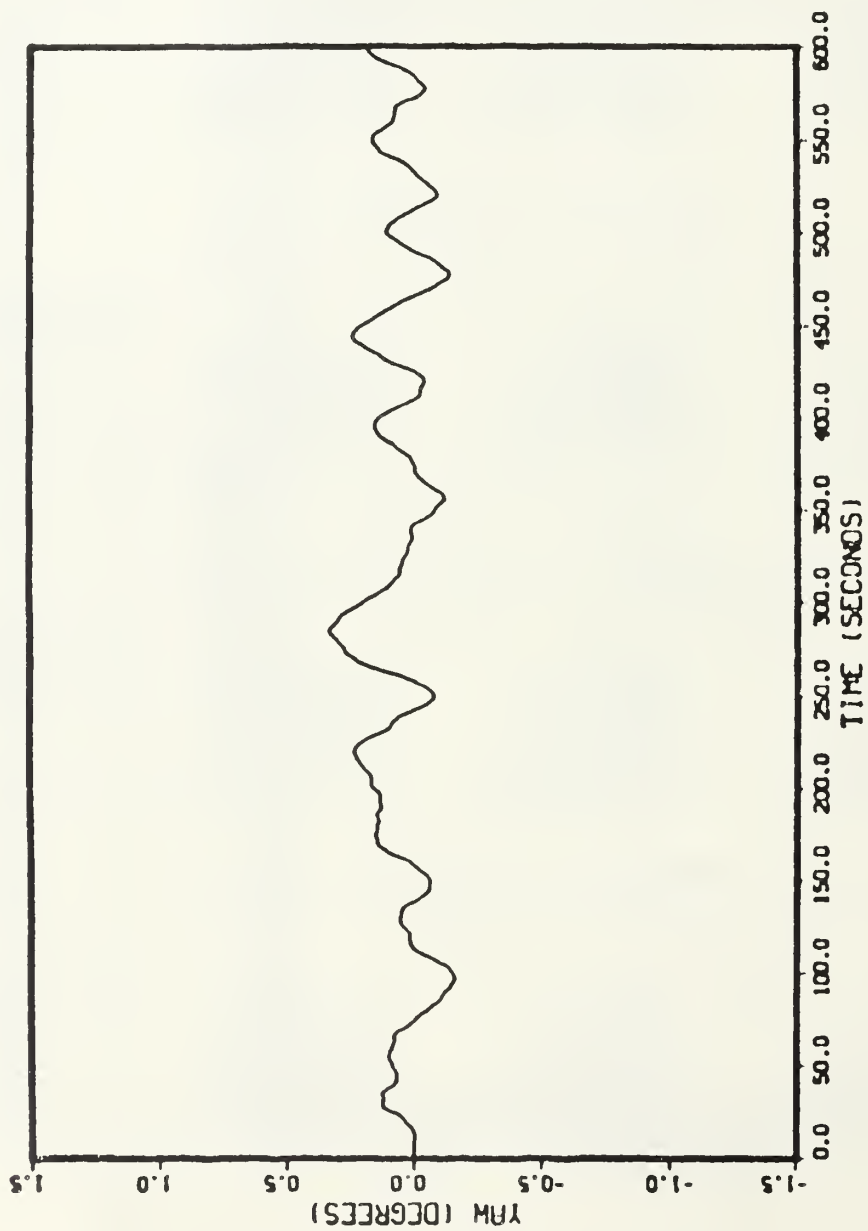


Figure 5.2 Yaw vs Time, Sea State 6.
Encounter Frequency 0.75 Rads Per sec, Encounter Angle 30°

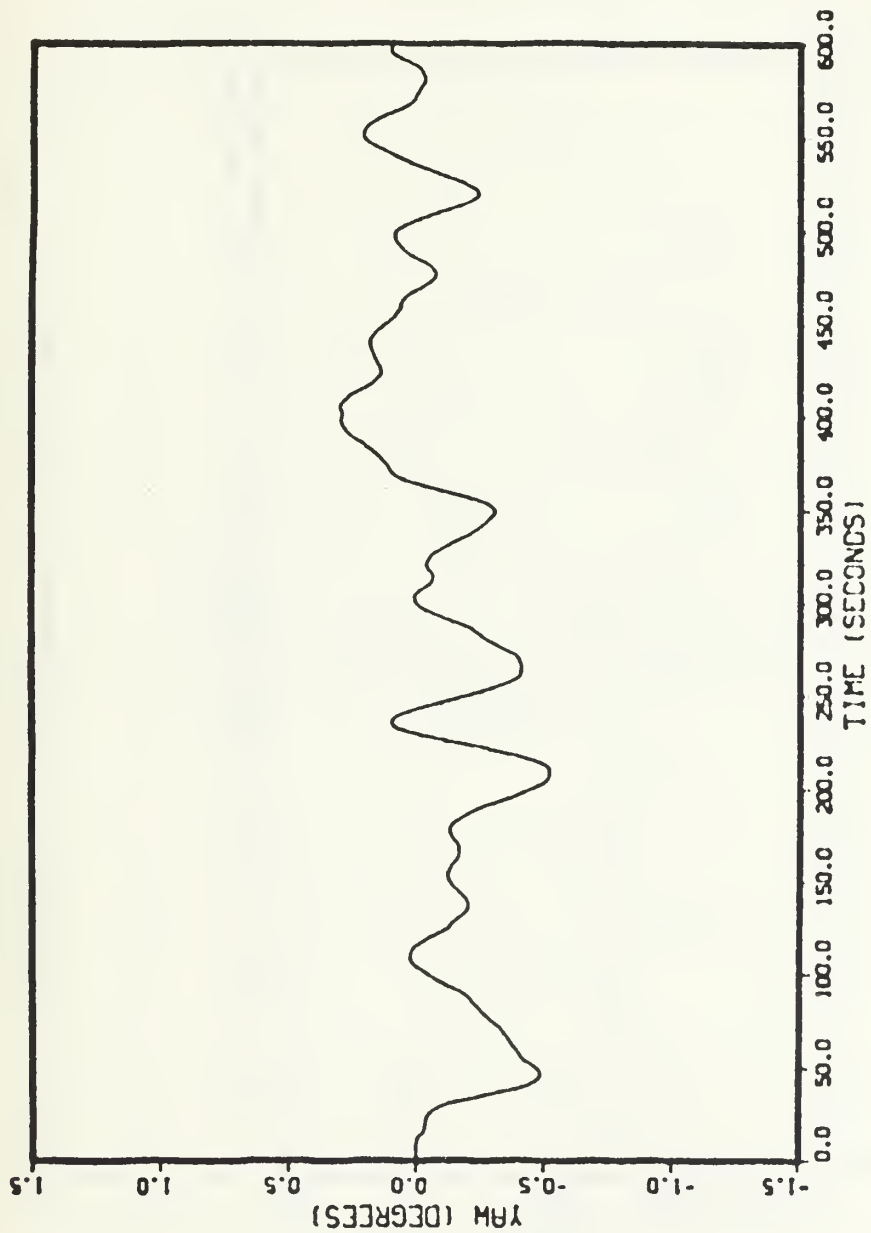


Figure 5.3 Yaw vs Time, Sea State 7.
Encounter Frequency 0.75 Rads Per Sec, Encounter Angle 30°

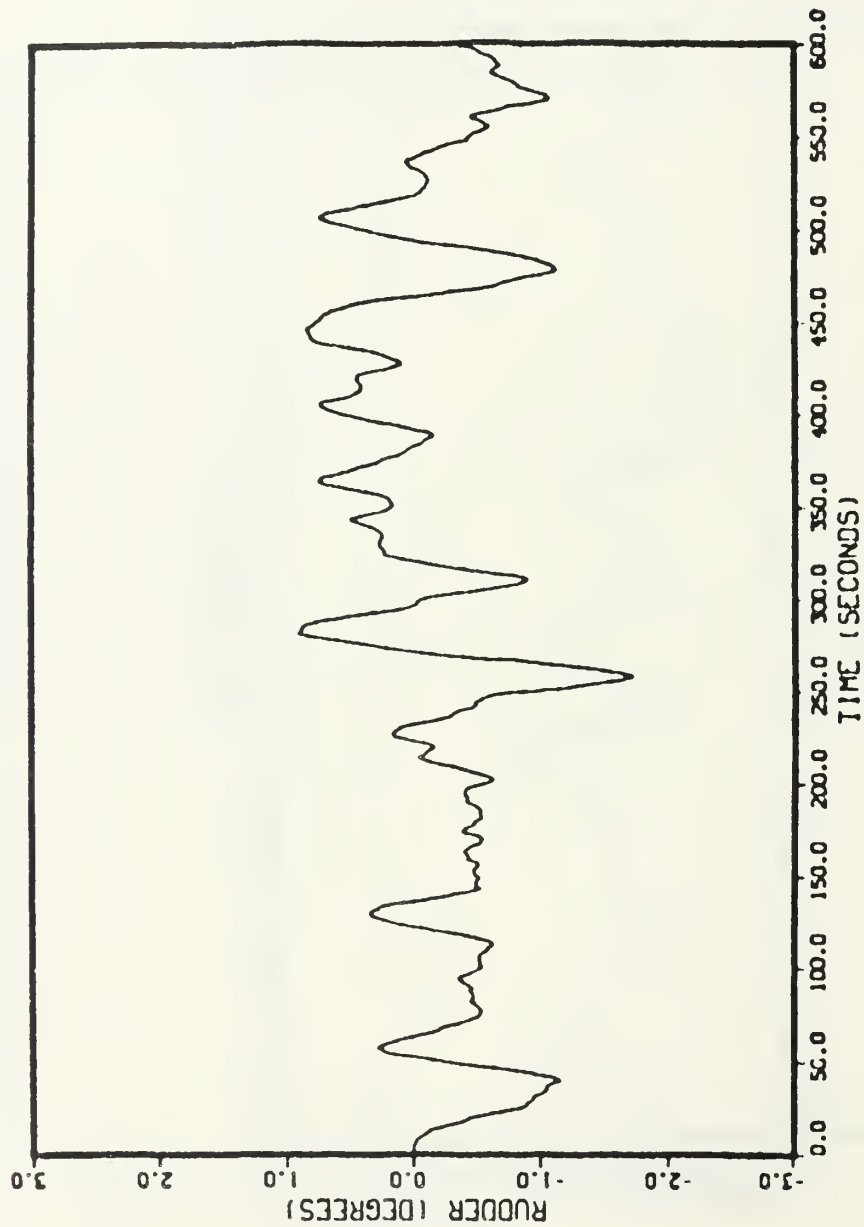


Figure 5.4 Rudder vs Time, Sea State 4.
Encounter Frequency 0.75 Rads Per Sec, Encounter Angle 30°

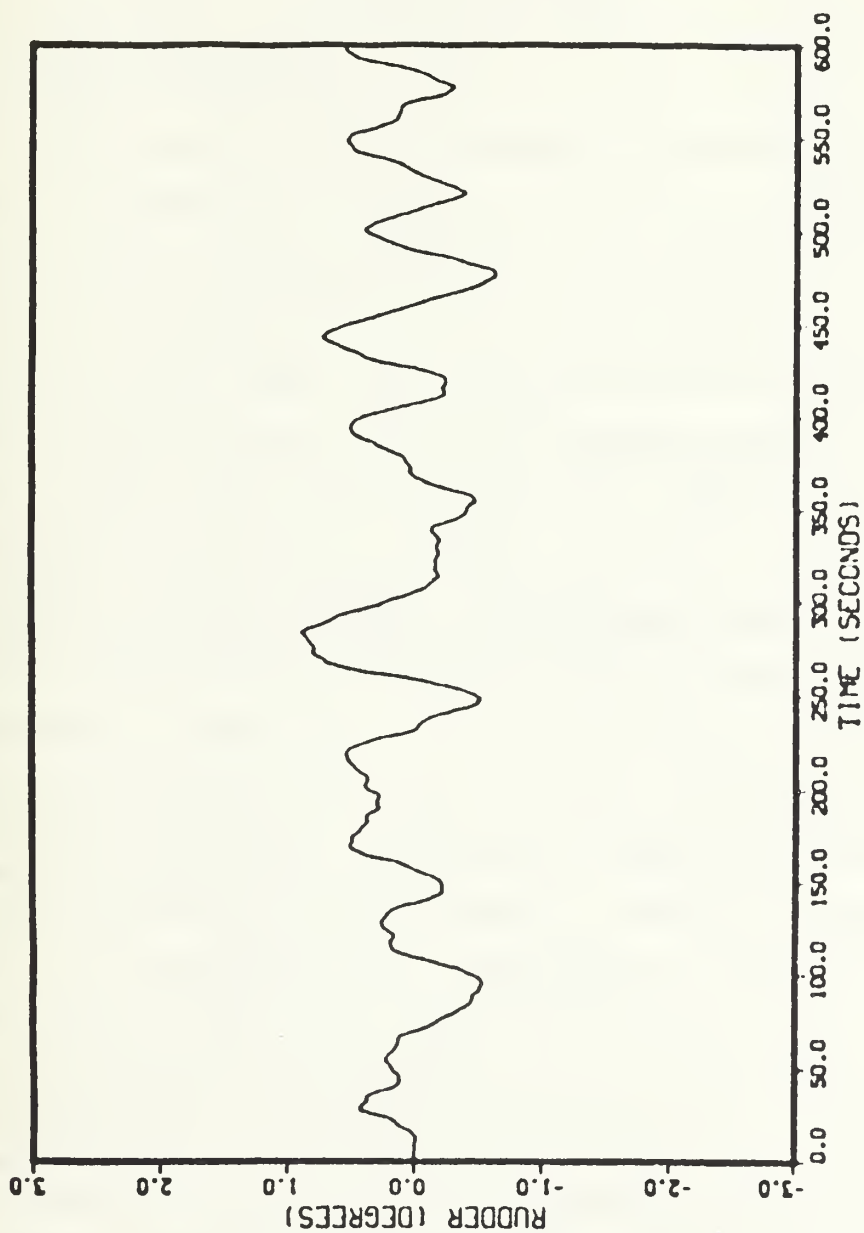


Figure 5.5 Rudder vs Time, Sea State 6.
Encounter Frequency 0.75 Rads Per Sec, Encounter Angle 30°

VI. ADAPTIVE CONTROL

A. STRUCTURE

When the ship is moving in a seaway, the controller parameters are changing due to alterations in the sea state and encounter angle. In addition we know that using fixed parameters for the controller over the entire spectrum, it is somewhat difficult to have an appropriate response of the system. The adjustment of the controller parameters during operation in a seaway, can be achieved by means of an adaptive control.

The adaptive controller can be built with digital circuits and analog components as well. Analog system hardware has to be designed for each specific requirement, and any new requirement involves changes to components. This is a time consuming task. However, for simple control requirements analog systems still have a possible economic advantage over digital systems [Ref. 11].

On the other hand, digital systems are immediately more attractive when control systems are required to carry out more and more complex tasks. The advent of microprocessors and associated components has enabled low cost microcomputers to be built. These no longer require special environments and are fully compatible with shipboard use. The advantages of microcomputer controls over other types are that they are extremely reliable particularly as relatively fewer components are required and hence they are smaller. Their capability is greater than comparable analog systems due to their ability to carry out more complex calculations. A major advantage is their flexibility while using standard hardware, being able to be reconfigured for changes in

system requirement without the need to alter the hardware. This flexibility is achieved by the programmed software which is stored in the memory of the computer.

An adaptive control scheme is indicated in Figure 6.1 and in Figure 6.2 we show analytically the components of what we call the 'Decision Generator'.

B. SEARCH ALGORITHM

The parameters corresponding to various environmental conditions (sailing modes) are sorted in a memory. When the sailing modes change, δ and ψ vary so that the value of the performance index changes from its theoretical value. This change is detected by the threshold detector.

If the threshold is too small the adaptive structure will try new conditions when it is not necessary and in the opposite case the adaptive structure might not adapt to new sailing modes.

Using the term threshold we want to make sure that only significant changes in the environmental conditions will be considered, otherwise the system will look for a new model too often.

When the threshold detects that a new set of parameters should be used the search algorithm will look for conditions close to the previous one because the external conditions are not expected to vary rapidly. Then a new optimal value of J is selected and must be matched with the performance index computed for the real ψ and δ .

Matching operation must be done after some delay ensuring that the conditions had an effect on the real cost function.

These new parameter values will be fed into the controller and function minimization subroutine as well.

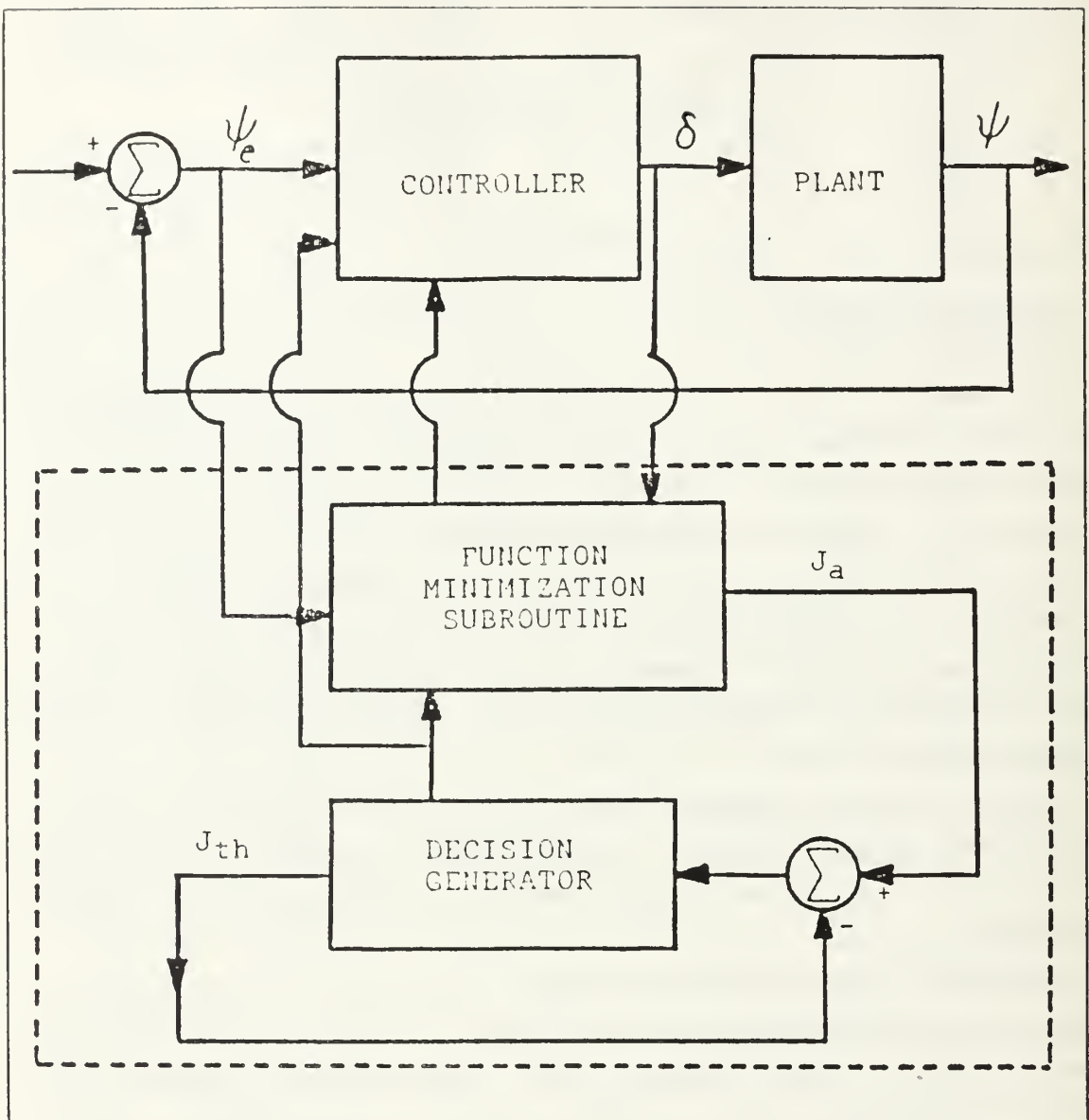


Figure 6.1 Adaptive Control Scheme

C. ADVANTAGES

- Using this adaptive scheme we don't use sensors which may be unrealistic and the use of predetermined filters which are so expensive can be avoided.

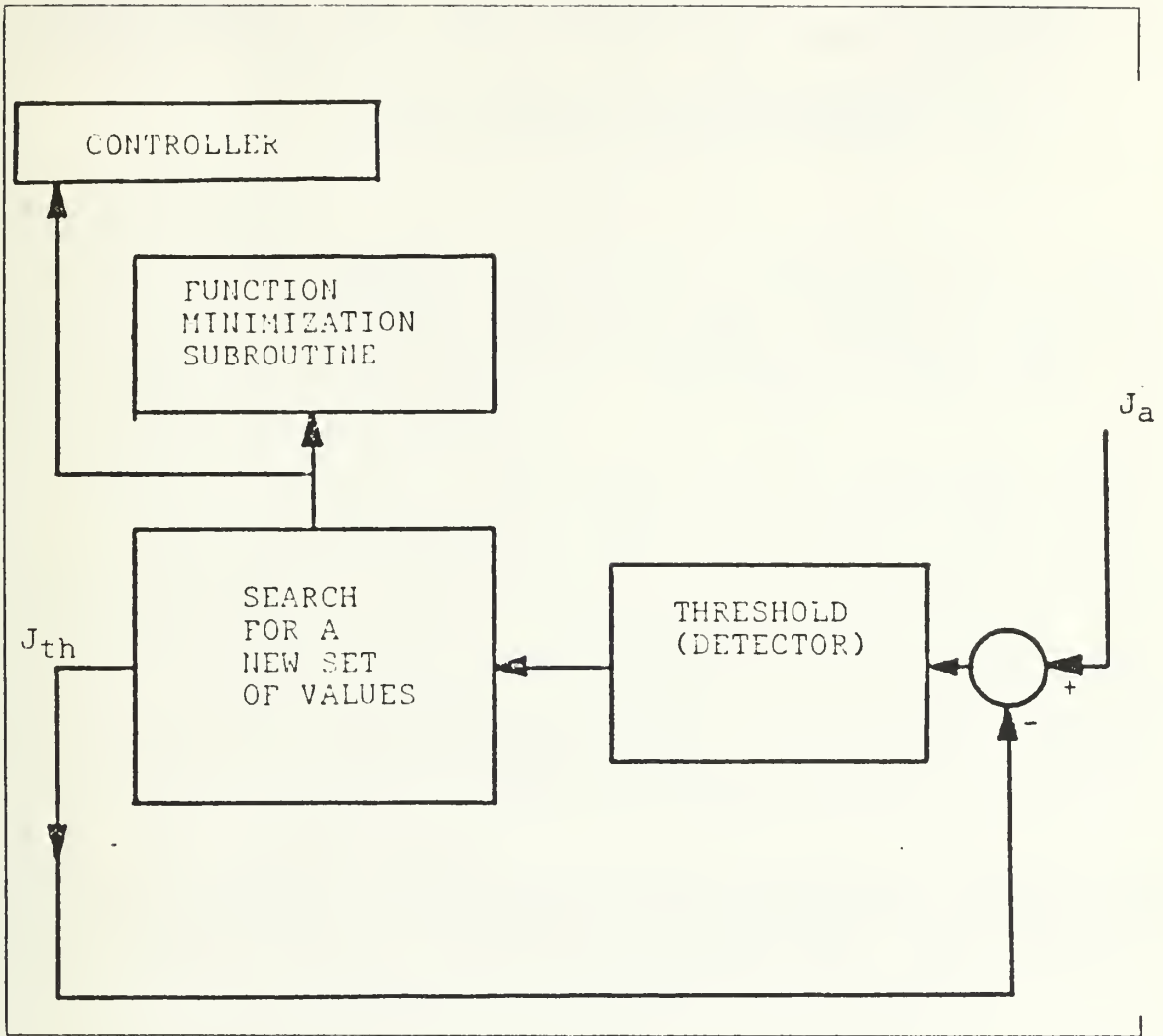


Figure 6.2 Decision Generator

- Provides a good choice for the function minimization subroutine to start its iteration algorithm and therefore we get the optimum values as quickly as possible.

D. DISADVANTAGES

- The search algorithm must be carefully determined.
- Since we don't include sensor's measurements there is no indications on how to perform the search. This

problem can be eliminated when the NAVSTAR/GLOBAL POSITION SYSTEM (GPS) will be able to provide precision navigation data.

VII. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

- A properly designed controller can minimize the rudder activity providing desired overseas heading as well, and therefore does result in substantial improvement in propulsion efficiency.
- Actual savings in fuel cannot yet be determined since there is no information available from the conventional autopilot and therefore there is no possibility for comparison.
- It is believed that the performance index used in this research is a fairly adequate function. Doubts arise from the weighting factor which is included and this because λ is based on assumptions and its accuracy is not certain.
- An adaptive controller which minimizes propulsion losses due to steering is needed when environmental conditions and ship characteristics change.
- Studying all the investigated sailing modes, it turns out that the cost surface is flat. As a consequence determination of the controller parameters does not require high accuracy.
- The study shows that the use of the third order ship Nomoto model is a reasonable choice instead of using the ship's equation of motion, which involves both the sway and yaw equations.
- It can be assumed from the work done in this research that some of the findings could have applicability to a number of ship types. However it is not possible to make inference, of a general nature concerning all ships

from the results of the SL-7 which represents a particular type of a particular class of ships.

B. RECOMMENDATIONS FOR FUTURE STUDY

- Additional work has to be done for obtaining optimum controller parameters under an expanded range of operating conditions. The more optimum controller parameter values available, the better the determination of the search algorithm recommended in the adaptive control scheme.
- A study including the surge equation in our ship model is recommended since in reality added resistance due to steering reduces ship's speed and so far we assumed constant speed. In addition with the use of the surge equation we can determine actual energy losses.
- Investigation of more advanced methods of adaptive control based on "on-line" determination of plant characteristics.
- So far we were interested in minimizing rudder and yawing activity to reduce propulsion losses using a particular performance criterion in open seas. Considering some other types of control such as automatic control for replenishment requires an investigation as to the suitability of the cost function, and a comparison with other potential cost functions.

APPENDIX A

DETERMINATION OF NOMOTO THIRD ORDER MODEL-BOXPLX

```
//PROGRA JOB (????,0356),'RESEARCH',CLASS=G
//*MAIN ORG=NPGVM1.????P
// EXEC FORTXCG,PARM.FORT='OPT(2)',IMSL=DP,REGION=1024K
//FORT.SYSIN DD *
C THIS PROGRAM WILL OBTAIN THE CONTROLLER OPTIMAL GAINS.
C IT IS REFERENCED IN CHAPTER 5.
C IN ORDER TO PERFORM SIMULATION ONLY WHEN GAINS HAVE BEEN
C OBTAINED CHANGE XS(*) TO X(*) AND DELETE XU(*),AND XL(*).
      DIMENSION XS(5),XU(5),XL(5)
      XS(1)=1.7466650
      XS(2)=35.2978973
      XS(3)=22.2485657
      XS(4)=13.6511078
      XS(5)=22.1172638
C  XS(I) IS THE STARTING GUESS
C  XL(I) IS THE LOWER LIMIT FOR THE I'TH VARIABLE
C  XU(I) IS THE UPPER LIMIT FOR THE I'TH VARIABLE
      XL(1)=0.1
      XU(1)=4.0
      XL(2)=0.1
      XU(2)=80.0
      XL(3)=1.0
      XU(3)=50.0
      XL(4)=1.0
      XU(4)=30.0
      XL(5)=1.0
      XU(5)=50.0
C  A DESCRIPTION OF THE FOLLOWING PARAMETERS
C  IS DISCUSSED IN BOXPLX
      R=9./13.
```

```

        NTA=1000
        NPR=100
        NAV=0
        NV=5
        IP=0
C   THE FOLLOWING STATEMENT MUST BE CHANGED TO
C   CALL PLANT(X)
C   IF ONLY SIMULATION IS WANTED
        CALL BOXPLX(NV,NAV,NPR,NTA,R,XS,IP,XU,XL,YMN,IER)
        WRITE (6,25)
25    FORMAT(1X,' OPTIMAL GAINS',/)
        DO 30 I=1,5
30    WRITE(6,40)I,XS(I)
40    FORMAT(1X,'X(',I2,')=' ,F14.7)
        STOP
        END
        SUBROUTINE PLANT(XX)
C   SUBROUTINE PLANT(XX) SIMULATES THE SHIP
        COMMON TDIFF
        REAL*8 L,L2,L3,L4,L5,L6
        REAL*8 X,XDOT,Y,YDOT,U,UDOT,V,VDOT,YAW,R,RDOT
        REAL*8 TIME,ETIME,XUDOT,XUU,XVR,XVV,XDD
        REAL*8 YV,YR,YD,YVVR,YVRR,YVVV,YRRR,YDDD,YVDOT
        REAL*8 NV,NR,ND,NVVR,NVRR,NVVV,NRRR,NDDD,NRDOT
        REAL*8 RHO,IZ,FX,FY,MZ,XP,MASS,DELT,MZI,RXI,WA,WE
        REAL*8 DYAW,YAWE,YAWC,ISE,ISR,LAMDA,D,RYR,RYI,MZR
        REAL*8 K1,T1,T2,D,X2,DX2,S,RX,RY,RZ,TX,TY,TZ,RXR
        REAL*8 T3,T4,X3,DX3,X4
        DIMENSION XX(5)
C
C   CLOSE LOOP ANALYSIS WITH FILTER
C
C   INITIAL CONDITIONS FOR INTEGRATION
C   SIMULATION END TIME IN SECONDS
        ETIME=600.0

```

```

TIME=0.0
ICOUNT=1
C INITIALIZE THE COST FUNCTION
ISE=0.0
ISR=0.0
TDIFF=0.0
LAMDA=8.128
C GAIN COEFFICIENTS TO BE OPTIMIZED
K1=XX(1)
T1=XX(2)
T2=XX(3)
T3=XX(4)
T4=XX(5)
C WRITE(6,1010) K1,T1,T2
C1010 FORMAT(1X,'K1 =',F15.7,'T1 =',F15.7,' T2 =',F15.7)
C X,XDOT,Y,YDOT ARE FIX COORDINATES ON EARTH
X=0.0
Y=0.0
XDOT=0.0
YDOT=0.0
C U,UDOT,V,VDOT ARE FIX COORDINATES ON SHIP
V=0.0
UDOT=0.0
VDOT=0.0
YAW=0.0
R=0.0
RDOT=0.0
C ORDERED SPEED IN FEET/SEC
C 38.82 FT/SEC=23 KNOTS
UC=38.82
C AT STEADY STATE ACTUAL SPEED (U) = COMMAND SPEED (UC)
U=UC
C D = RUDDER ANGLE
D=0.0
L=880.5

```

L2=L**2
L3=L*L*L
L4=L*L3
L5=L*L4
L6=L*L5

C SEA DISTURBANCE

C FORCES IN X,Y DIRECTION COMPUTED IN FORCES

C MOMENTS IN Z

FX=0.

FY=0.

MZ=0.

RXR=-0.15744D+05

RXI=-0.19950D+06

RYR=0.52365D+04

RYI=0.18699D+06

MZR=-0.29870D+08

MZI=-0.35751D+07

C RXR=-0.50230D+04

C RXI=0.12712D+05

C RYR=0.35290D+04

C RYI=-0.31909D+05

C MZR=0.38826D+07

C MZI=-0.64313D+07

C RXR=0.28540D+04

C RXI=-0.99574D+04

C RYR=-0.85441D+04

C RYI=0.39595D+05

C MZR=-0.13014D+08

C MZI=0.11348D+08

C RXR=-0.75642D+04

C RXI=0.83497D+04

C RYR=0.23379D+05

C RYI=-0.81502D+05

C MZR=0.28622D+07

C MZI=-0.19388D+08


```

C      RXR=-0.37916D+04
C      RXI=0.16381D+04
C      RYR=-0.76647D+05
C      RYI=-0.37685D+05
C      MZR=-0.83915D+07
C      MZI=-0.53176D+07
      RX=DSQRT(RXR**2+RXI**2)
      RY=DSQRT(RYR**2+RYI**2)
      RZ=DSQRT(MZR**2+MZI**2)
      TX=DATAN(RXI/RXR)
      TY=DATAN(RYI/RYR)
      TZ=DATAN(MZI/MZR)
C  SIGNIFICANT WAVE HEIGHT; SEA STATE 1-5,2-10,3-15
C  4-17.5,5-22.5,6-27,7-35,8-42,9-60
      WA=17.5
C  ENCOUNTER FREQUENCY .1,.2,.3,.4,.5,.6,.75,1.0,1.5,2.5
      WE=0.2
C  HYDRODYNAMIC COEFFICIENTS ARE INSERTED HERE AS
c  PARAMETERS
      RHO=1.9876
      MASS=(.0044)*(.5*RHO*L3)
      IZ=(0.00028)*(.5*RHO*L5)
      YAWC=0.0
      X2=0.0
      DX2=0.0
      X3=0.0
      DX3=0.0
200 CONTINUE
      S=DSQRT(U**2+V**2)
C  INPUT YAW COMMAND
      YAWC=0.0
      IF (TIME.GE.0.0) YAWC=0.0
C  ERROR SIGNAL TO DRIVE RUDDER(YAW ACTUAL - YAW ORDERED)
C  ( COMPENSATOR FILTER )
      YAWC=YAW - YAWC

```

```

DX2=(YAWE-X2)/T2
X4=K1*(T1*DX2+X2)
DX3=(X4-X3)/T4
D=(T3*DX3+X4)
C  AXIAL FORCE HYDRODYNAMIC COEFFICIENTS (SURGE)
C  XUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED
C  FOR DIFFERENT ENCOUNTER ANGLE , SPEED ,
C  ENCOUNTER FREQUENCY
      XUDOT=(-.0001)*(.5*RHO*L3)
      XU=(-0.0253)*(.5*RHO*L2*S)
      XUU=(-0.0003)*(.5*RHO*L2)
      XVR=(0.0039)*(.5*RHO*L3)
      XVV=(-.0012)*(.5*RHO*L2)
      XDD=(-0.0005)*(.5*RHO*L2*S**2)
C  LATERAL FORCE HYDRODYNAMIC COEFFICIENTS (SWAY)
C      YV=(-0.00758)*(.5*RHO*L2*S)
      YR=(0.0023)*(.5*RHO*L3*S)
      YD=(0.00145)*(.5*RHO*L2*S**2)
      YVVR=(0.01)*(.5*RHO*L3/S)
      YVRR=(-0.008)*(.5*RHO*L4/S)
      YVVV=(-0.03)*(.5*RHO*L2/S)
      YRRR=(0.003)*(.5*RHO*L5/S)
      YDDD=(-0.0005)*(.5*RHO*L2*S**2)
C  YUDOT IS THE ADDED MASS TERM WHICH MUST BE
C  CHANGED FOR DIFFERENT ENCOUNTER ANGLE , SPEED ,
C  ENCOUNTER FREQUENCY
C      YVDOT=(-0.0039)*(.5*RHO*L3)
C  SPEED=23 KNOTS, ENCOUNTER ANGLE = 30 , ENCOUNTER
C  FREQUENCY =0.2
      YVDOT=-0.30908D+07
      YV=-0.81271D+04
C      YVDOT=-0.36185D+07
C      YV=-0.24757D+06
C      YVDOT=-0.32890D+07
C      YV=-0.11775D+07

```

```

C      YVDOT=-0.23038D+07
C      YV=-0.18267D+07
C      YVDOT=-0.59800D+06
C      YV=-0.13260D+07
C      MOMENT ABOUT Z-AXIS HYDRODYNAMIC COEFFICIENTS (YAW)
      NV=(-0.00213)*(.5*RHO*L3*S)
C      NR=(-0.00105)*(.5*RHO*L4*S)
      ND=(-0.0007)*(.5*RHO*L3*S**2)
      NVVR=(-0.015)*(.5*RHO*L4/S)
      NVRR=(-0.008)*(.5*RHO*L5/S)
      NVVV=(0.01)*(.5*RHO*L3/S)
      NRRR=(-0.006)*(.5*RHO*L6/S)
      NDDD=(0.0001)*(.5*RHO*L3*S**2)
C      NRDOT IS THE ADDED INERTIA TERM WHICH MUST BE
C      CHANGED FOR DIFFERENT ENCOUNTER ANGLE , SPEED ,
C      ENCOUNTER FREQUENCY
C
C      NRDOT=(-0.00027)*(.5*RHO*L5)
C      SPEED=23 KNOTS, ENCOUNTER ANGLE = 90 , ENCOUNTER
C      FREQUENCY =0.2
      NRDOT=-0.26251D+12
      NR=-0.53637D+09
C      NRDOT=-0.20125D+12
C      NR=-0.94970D+10
C      NRDOT=-0.18671D+12
C      NR=-0.46860D+11
C      NRDOT=-0.14518D+12
C      NR=-0.87538D+11
C      NRDOT=-0.37261D+11
C      NR=-0.69856D+11
C      REGULAR WAVE SEA STATE
      FX=WA*RX*DCOS(WE*TIME+TX)
      FY=WA*RY*DCOS(WE*TIME+TY)
      MZ=WA*RZ*DCOS(WE*TIME+TZ)
C      U ACTUAL SPEED

```

```

C UC COMMANDED SPEED
C XP = PROPELLER THRUST
  XP=-XUU*UC**2
C EQUATIONS OF MOTION
C   UDOT=( (XVR + MASS)*V*R + XUU*U**2 + XVV*V**2
C   1 + XDD*D*D + FX + XP )/(MASS-XUDOT)
  VDOT=(YV*V + (YR-MASS*U)*R + YD*D + YVVR*V**2*R
  1 + YVRR*V*R**2 + YRRR*R**3
  2 + YDDD*D**3 + FY )/(MASS-YVDOT)
  RDOT=( NV*V + NR*R + ND*D + NVVR*V**2*R
  1 + NVRR*V*R**2 + NVVV*V**3
  2 + NRRR*R**3 + NDDD*D**3 + MZ )/(IZ-NRDOT)
C WHEN TO PRINTOUT
  IF (ICOUNT.EQ.11) GO TO 50
  GO TO 300
C CONVERT RADIANS TO DEGREES
50 YAWDEG= YAW*57.296
  RDEG=R*57.296
  RDDEG=RDOT*57.296
  DDEG=D*57.296
  YAWC=YAWC*57.296
C   WRITE (6,100) TIME,XP,X,XDOT,Y,YDOT
C   1 ,UC,U,UDOT,V,VDOT,YAWC,YAWDEG,RDEG,RDDEG,DDEG
100 FORMAT(1X,'TIME=',F8.3,' SEC  XP=',F10.2,' LBF
  1 X=',F8.2,
  1 ' FT  XDOT=',F8.4,' FT/SEC  Y=',F8.2,' FT  YDOT='
  1 ,F8.4,' FT/SEC
  1 ',/,2X,' UC=',F8.4,' FT/SEC  U=',F8.4,' FT/SEC
  1 UDOT=',F10.6,
  1 ' FT/SEC**2  V=',F8.4,' FT/SEC  VDOT=',F10.6,
  1 ' FT/SEC**2'
  1 ',/,2X,' YAWC=',F8.4,' DEG  YAW='
  1 ,F15.7,' DEG  YAW RATE=',F15.7,' DEG/SEC
  1 YAW ACCEL=',F15.7,'
  1 DEG/SEC**2',/,2X,' RUDDER =',F15.7,' DEG ',/)

```

```

        ICOUNT=1
C   TEST IF WANT TO STOP
    300   IF (TIME.GE.ETIME) GO TO 400
C   INTEGRATION STEP SIZE DELT
        DELT=1.0
C   INTEGRATION
        U=U+UDOT*DELT
        V=V+VDOT*DELT
        R=R+RDOT*DELT
        YAW=YAW+R*DELT
        X2=X2+DX2*DELT
        X3=X3+DX3*DELT
C   CONVERT SHIP TO FIXED COORDINATES ON EARTH
C       XDOT=U*DCOS(YAW)-V*DSIN(YAW)
C       YDOT=U*DSIN(YAW)+V*DCOS(YAW)
C       X=X+XDOT*DELT
C       Y=Y+YDOT*DELT
        TIME=TIME+DELT
        ICOUNT=ICOUNT+1
        ISE=ISE + LAMDA*YAW**2
        ISR=ISR + D**2
        GO TO 200
C   J=TDIFF= COST FUNCTION
    400   TDIFF=ISE+ISR
        WRITE(6,500) ISE,ISR,TDIFF,K1,T1,T2,T3,T4
    500   FORMAT(' ',1X,'TOTAL=',F15.7,2X,
    1      'K1=',F15.7,2X,'T1=',F15.7,2X,'T2=',F15.7,2X,
    1      'T3=',F15.7,2X,'T4=',F15.7)
        RETURN
        END
        SUBROUTINE BOXPLX (NV,NAV,NPR,NTZ,RZ,XS,IP,BU,BL,
    1      LYMN,IER)
C
        DIMENSION V(50,50), FUN(50), SUM(25), CEN(25),
    1      1XS(NV),BU(NV),BL(NV)

```

C

```
KV = 5
EP = 1.E-6
NTA = 2000
IF (NTZ.GT.0) NTA = NTZ
R = RZ
IF (R.LE.0..OR.R.GE.1.) R=1./3.
NVT = NV+NAV
```

C

C TOTAL VARS, EXPLICIT PLUS IMPLICIT

```
NT = 0
```

C

CURRENT TRIAL NO.

```
NPT = 0
```

C

CURRENT NO. OF PERMISSIBLE TRIALS

```
NTFS = 0
```

C

CURRENT NO. OF TIMES F HAS BEEN ALMOST UNCHANGED

C

C

CHECK FEASIBILITY OF START POINT

C

```
DO 4 I=1,NV
VT = XS(I)
IF (BL(I).LE.VT) GO TO 1
II = -I
VT = BL(I)
GO TO 2
1 IF (BU(I).GE.VT) GO TO 3
II = I
VT = BU(I)
2 IF (NPR.GT.0) WRITE (6,49) II
3 V(I,1) = VT
CEN(I) = VT
IF (IP.EQ.1) GO TO 4
BL(I) = BL(I)+AMAX1(EP,EP*ABS(BL(I)))
BU(I) = BU(I)-AMAX1(EP,EP*ABS(BU(I)))
4 SUM(I) = VT
```

```

C
C
      NCE = 1
C      NUMBER OF CONSTRAINT EVALUATIONS
      I = 1
      IF (KE(V(1,1)).EQ.0) GO TO 5
      IF (NPR.LE.0) GO TO 12
      WRITE (6,50)
      GO TO 12
5 NFE = 1
C
C      NUMBER OF VERTICES (K) = 2 TIMES NO. OF VARIABLES.
      K = 2*NV
C
C      NUMBER OF DISPLACEMENTS ALLOWED.
      NLIM = 5*NV+10
C
C      NUMBER OF CONSECUTIVE TRIALS WITH UNCHANGED
c      FE TO TERMINATE.
      NCT = NLIM+NV
      ALPHA = 1.3
      FK = K
      FKM = FK-1.
      BETA = ALPHA+1.
C
C      INSURE SEED OF RANDOM NUMBER GENERATOR IS ODD.
      IQR = R*1.E7
      IF (MOD(IQR,2).EQ.0) IQR=IQR+101
C
C      SET UP INITIAL VERTICES
      FUN(1) = FE(V(1,1))
      YMN = FUN(1)
6 FI = 1.
      FUNOLD = FUN(1)
C

```



```

        DO 15 I=2,K
        FI = FI+1.
        LIMIT = 0
7      LIMIT = LIMIT+1
C
C      END CALCULATION IF FEASIBLE CENTROID CANNOT BE FOUND.
        IF (LIMIT.GE.NLIM) GO TO 11
C
        DO 8 J=1,NV
C
C      RANDOM NUMBER GENERATOR (RANDU)
        IQR = IQR*65539
        IF (IQR.LT.0) IQR = IQR+2147483647+1
        RQX = IQR
        RQX = RQX*.4656613E-9
        V(J,I) = BL(J)+RQX*(BU(J)-BL(J))
        IF (IP.EQ.1) V(J,I)=AINT(V(J,I)+.5)
8      CONTINUE
C
        DO 10 L=1,NLIM
        NCE = NCE+1
        IF (KE(V(1,I)).EQ.0) GO TO 13
C
        DO 9 J=1,NV
        VT = .5*(V(J,I)+CEN(J))
        IF (IP.EQ.1) VT = AINT(VT+.5)
        V(J,I) = VT
9      CONTINUE
C
10     CONTINUE
C
11    IF (NPR.LE.0) GO TO 12
        WRITE (6,51) I
        CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,I,FUN,CEN,I)
12    IER = -1

```

```

        GO TO 48
C
13 DO 14 J=1,NV
    SUM(J) = SUM(J)+V(J,I)
14 CEN(J) = SUM(J)/FI
C
C TRY TO ASSURE FEASIBLE CENTROID FOR STARTING.
    NCE = NCE+1
    IF (KE(CEN).EQ.0) GO TO 60
    SUM(J) = SUM(J) -V(J,I)
    GO TO 7
60 NFE = NFE+1
    FUN(I) = FE(V(1,I))
15 CONTINUE
C
C END OF LOOP SETTING OF INITIAL COMPLEX.
    IF (NPR.LE.0) GO TO 17
    CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,0)
C
C FIND THE WORST VERTEX, THE 'J'TH.
    J = 1
C
    DO 16 I=2,K
        IF (FUN(J).GE.FUN(I)) GO TO 16
        J = I
16 CONTINUE
C
C BASIC LOOP. ELIMINATE EACH WORST VERTEX
C IN TURN. IT MUST BECOME NO LONGER WORST,NOT
C MERELY IMPROVED. FIND NEXT-TO-WORST VERTEX,
C THE 'JN'TH ONE.
17 JN = 1
    IF (J.EQ.1) JN = 2
C
    DO 18 I=1,K

```

```

      IF (I.EQ.J) GO TO 18
      IF (FUN(JN).GE.FUN(I)) GO TO 18
      JN = I
18  CONTINUE
C
C  LIMIT = NUMBER OF MOVES DURING THIS TRIAL TOWARD
C  THE CENTRIOD DUE TO FUNCTION VALUE.
      LIMIT = 1
C
C  COMPUTE CENTROID AND OVER REFLECT WORST VERTEX.
C
      DO 19 I=1,NV
      VT = V(I,J)
      SUM(I) = SUM(I)-VT
      CEN(I) = SUM(I)/FKM
      VT = BETA*CEN(I)-ALPHA*VT
      IF (IP.EQ.1) VT = AINT(VT+.5)
C
C  INSURE THE EXPLICIT CONSTRAINTS ARE OBSERVED.
19  V(I,J) = AMAX1(AMIN1(VT,BU(I)),BL(I))
C
      NT = NT+1
C
C  CHECK FOR IMPLICIT CONSTRAINT VIOLATION.
C
20  DO 25 N=1,NLIM
      NCE = NCE+1
      IF (KE(V(1,J)).EQ.0) GO TO 26
C
C  EVERY 'KV'TH TIME, OVER-REFLECT THE OFFENDING
C  VERTEX THROUGH THE BEST VERTEX.
      IF (MOD(N,KV).NE.0) GO TO 22
      CALL FBV (K,FUN,M)
C
      DO 21 I=1,NV

```

```

      VT = BETA*V(I,M)-ALPHA*V(I,J)
      IF (IP.EQ.1) VT = AINT(VT+.5)
21  V(I,J) = AMAX1(AMIN1(VT,BU(I)),BL(I))
C
      GO TO 24
C
C  CONSTRAINT VIOLATION:  MOVE NEW POINT TOWARD CENTROID.
C
22  DO 23 I=1,NV
      VT = .5*(CEN(I)+V(I,J))
      IF (IP.EQ.1) VT = AINT(VT+.5)
      V(I,J) = VT
23  CONTINUE
C
24  NT = NT+1
25  CONTINUE
C
      IER = 1
C
C  CANNOT GET FEASIBLE VERTEX BY MOVING TOWARD CENTROID,
C  OR BY OVER-REFLECTING THRU THE BEST VERTEX.
      IF (NPR.LE.0) GO TO 42
      WRITE (6,52) NT,J
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,J)
      GO TO 42
C
C  FEASIBLE VERTEX FOUND,EVALUATE THE OBJECTIVE FUNCTION.
26  NFE = NFE+1
      FUNTRY = FE(V(1,J))
C
C  TEST TO SEE IF FUNCTION VALUE HAS NOT CHANGED.
      AFO = ABS(FUNTRY-FUNOLD)
      AMX = AMAX1(ABS(EP*FUNOLD),EP)
C
C  ACTIVATE THE FOLLOWING TWO STATEMENTS

```

```

C   FOR DIAGNOSTICS PURPOSES ONLY.
C   WRITE (6,99) J,AFO,AMX,FUNTRY,FUNOLD,FUN(J),
C   1FUN(JN),NTFS,N
C 99 FORMAT (1X,I3,6E15.7,2I5)
      IF (AFO.GT.AMX) GO TO 27
      NTFS = NTFS+1
      IF (NTFS.LT.NCT) GO TO 28
      IER = 0
      IF (NPR.LE.0) GO TO 42
      WRITE (6,53) K
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,0)
      GO TO 42
27 NTFS = 0
C
C   IS THE NEW VERTEX NO LONGER WORST?
28 IF (FUNTRY.LT.FUN(JN)) GO TO 34
C
C   TRIAL VERTEX IS STILL WORST; ADJUST TOWARD CENTROID.
C   EVERY 'KV'TH TIME, OVER-REFLECT THE OFFENDING
C   VERTEX THROUGH THE BEST VERTEX.
      LIMIT = LIMIT+1
      IF (MOD(LIMIT,KV).NE.0) GO TO 30
      CALL FBV (K,FUN,M)
C
      DO 29 I=1,NV
      VT = BETA*V(I,M)-ALPHA*V(I,J)
      IF (IP.EQ.1) VT = AINT(VT+.5)
29 V(I,J) = AMAX1(AMIN1(VT,BU(I)),BL(I))
C
      GO TO 32
C
30 DO 31 I=1,NV
      VT = .5*(CEN(I)+V(I,J))
      IF (IP.EQ.1) VT = AINT(VT+.5)
      V(I,J) = VT

```

```

31 CONTINUE
C
32 IF (LIMT.LT.NLIM) GO TO 33
C
C CANNOT MAKE THE 'J'TH VERTEX NO LONGER WORST
C BY DISPLACING TOWARD OVER-REFLECTING
C THRU THE BEST VERTEX.
    IER = 2
    IF (NPR .LE. 0) GO TO 42
    WRITE (6,52) NT, J
    CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,J)
    GO TO 42
33 NT = NT+1
    GO TO 20
C
C SUCCESS: WE HAVE A REPLACEMENT FOR VERTEX J.
34 FUN(J) = FUNTRY
    FUNOLD = FUNTRY
    NPT = NPT+1
C
C EVERY 100'TH PERMISSIBLE TRIAL, RECOMPUTE
C CENTRIOD SUMMATION TO AVOID CREEPING ERROR.
    IF (MOD(NPT,100).NE.0) GO TO 37
C
    DO 36 I=1,NV
        SUM(I) = 0.
C
    DO 35 N=1,K
35 SUM(I) = SUM(I)+V(I,N)
C
    CEN(I) = SUM(I)/FK
36 CONTINUE
C
    LC = 0
    GO TO 39

```

```

C
37 DO 38 I=1,NV
38 SUM(I) = SUM(I)+V(I,J)
C
    LC = J
C
39 IF (NPR.LE.0) GO TO 40
    IF (MOD(NPT,NPR).NE.0) GO TO 40
C
    CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,CEN,LC)
C
C HAS THE MAX. NUMBER OF TRIALS BEEN REACHED
C WITHOUT CONVERGENCE?
C IF NOT, GO TO NEW TRIAL.
40 IF (NT.GE.NTA) GO TO 41
C
C NEXT-TO-WORST VERTEX NOW BECOMES WORST.
    J = JN
    GO TO 17
41 IER = 3
    IF (NPR.GT.0) WRITE (6,54)
C
C COLLECTOR POINT FOR ALL ENDINGS.
C 1) CANNOT DEVELOP FEASIBLE VERTEX. IER = 1
C 2) CANNOT DEVELOP A NO-LONGER-WORST VERTEX. IER = 2
C 3) FUNCTION VALUE UNCHANGED FOR K TRIALS. IER = 0
C 4) LIMIT ON TRIALS REACHED. IER = 3
C 5) CANNOT FIND FEASIBLE VERTEX AT START. IER = -1
42 CONTINUE
C
C FIND BEST VERTEX.
    CALL FBV (K,FUN,M)
    IF (IER.GE.3) GO TO 44
C
C RESTART IF THIS SOLUTION IS SIGNIFICANTLY BETTER

```

```

C   THAN THE PREVIOUS, OR IF THIS IS THE FIRST TRY.
      IF (NPR.LE.0) GO TO 43
      WRITE (6,55) (M,YMN,FUN(M))
43  IF (FUN(M).GE.YMN) GO TO 47
      IF (ABS(FUN(M)-YMN).LE.AMAX1(EP,EP*YMN)) GO TO 47
C
C   GIVE IT ANOTHER TRY UNLESS LIMIT ON TRIALS REACHED.
44  YMN = FUN(M)
      FUN(1) = FUN(M)
C
      DO 45 I=1,NV
      CEN(I) = V(I,M)
      SUM(I) = V(I,M)
45  V(I,1) = V(I,M)
C
      DO 46 I=1,NVT
46  XS(I) = V(I,M)
C
      IF (IER.LT.3) GO TO 6
47  IF (NPR.LE.0) GO TO 48
      CALL BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FUN,V(1,M),-1)
      WRITE (6,56) FUN(M)
48  RETURN
C
49  FORMAT (50H0INDEX AND DIRECTION OF
      1OUTLYING VARIABLE AT STARTI5)
50  FORMAT (50H0IMPLICIT CONSTRAINT
      1VIOLATED AT START. DEAD END.)
51  FORMAT ('0CANNOT FIND FEASIBLE',I4,'TH
      1VERTEX OR CENTROID AT START.')
52  FORMAT (10H0AT TRIAL I4,54H CANNOT FIND
      1FEASIBLE VERTEX WHICH IS NO LONGER
      1WORST,I4,15X,'RESTART FROM BEST VERTEX.')
53  FORMAT (40H0FUNCTION HAS BEEN ALMOST
      1UNCHANGED FOR I5,7H TRIALS)

```



```

54 FORMAT (27HOLIMIT ON TRIALS EXCEEDED. )
55 FORMAT ('OBEST VERTEX IS NO.',I3,'
1 OLD MIN WAS 'E15.7', NEW MIN IS ',E15.7)
56 FORMAT ('OMIN OBJECTIVE FUNCTION IS ',E15.7)
END
SUBROUTINE FBV (K,FUN,M)
DIMENSION FUN(50)
M = 1
C
DO 1 I=2,K
IF (FUN(M).LE.FUN(I)) GO TO 1
M = I
1 CONTINUE
C
RETURN
END
SUBROUTINE BOUT (NT,NPT,NFE,NCE,NV,NVT,V,K,FN,C,IK)
DIMENSION V(50,50), FN(50), C(25)
WRITE (6,4) NT,NPT,NFE,NCE
C
DO 1 I=1,K
WRITE (6,5) FN(I),(V(J,I),J=1,NV)
IF (NVT.LE.NV) GO TO 1
NVP = NV+1
WRITE (6,6) (V(J,I),J=NVP,NVT)
1 CONTINUE
C
IF (IK.NE.0) GO TO 2
C
WRITE (6,7) (C(I),I=1,NV)
RETURN
2 IF (IK.GE.0) GO TO 3
WRITE (6,8) (C(I),I=1,NV)
RETURN
3 WRITE (6,9) IK,(C(I),I=1,NV)

```

RETURN

C

```
4 FORMAT ('0NO. TOTAL TRIALS = ',I5,4X,  
1'NO. FEASIBLE TRIALS = ',I5,4X,'NO. FUNCTION  
1EVALUATIONS = ',I5,4X,'NO. CONSTRAINT EVALUATI  
IONS = ',I5/'0      FUNCTION VALUE',6X,'INDEPENDENT  
1VARIABLES/DEPENDENT OR IMPLICIT CONSTRAINTS')  
5 FORMAT (1H ,E18.7,2X,7E14.7/(21X,7E14.7))  
6 FORMAT (21X,7E14.7)  
7 FORMAT (10H0CENTROID 11X,7E14.7/(21X,7E14.7))  
8 FORMAT ('0 BEST VERTEX',7X,7E14.7/(21X,7E14.7))  
9 FORMAT ('0CENTROID LESS VX',I2,2X,7E14.7/  
1(21X,7E14.7))
```

END

FUNCTION FE(X)

DIMENSION X(5)

COMMON TDIFF

CALL PLANT(X)

FE=TDIFF

RETURN

END

FUNCTION KE(X)

DIMENSION X(5)

KE=0

RETURN

END

//GO.SYSIN DD *

/*

APPENDIX B
CONTROLLER DESIGN

A. CONTROLLER "C"

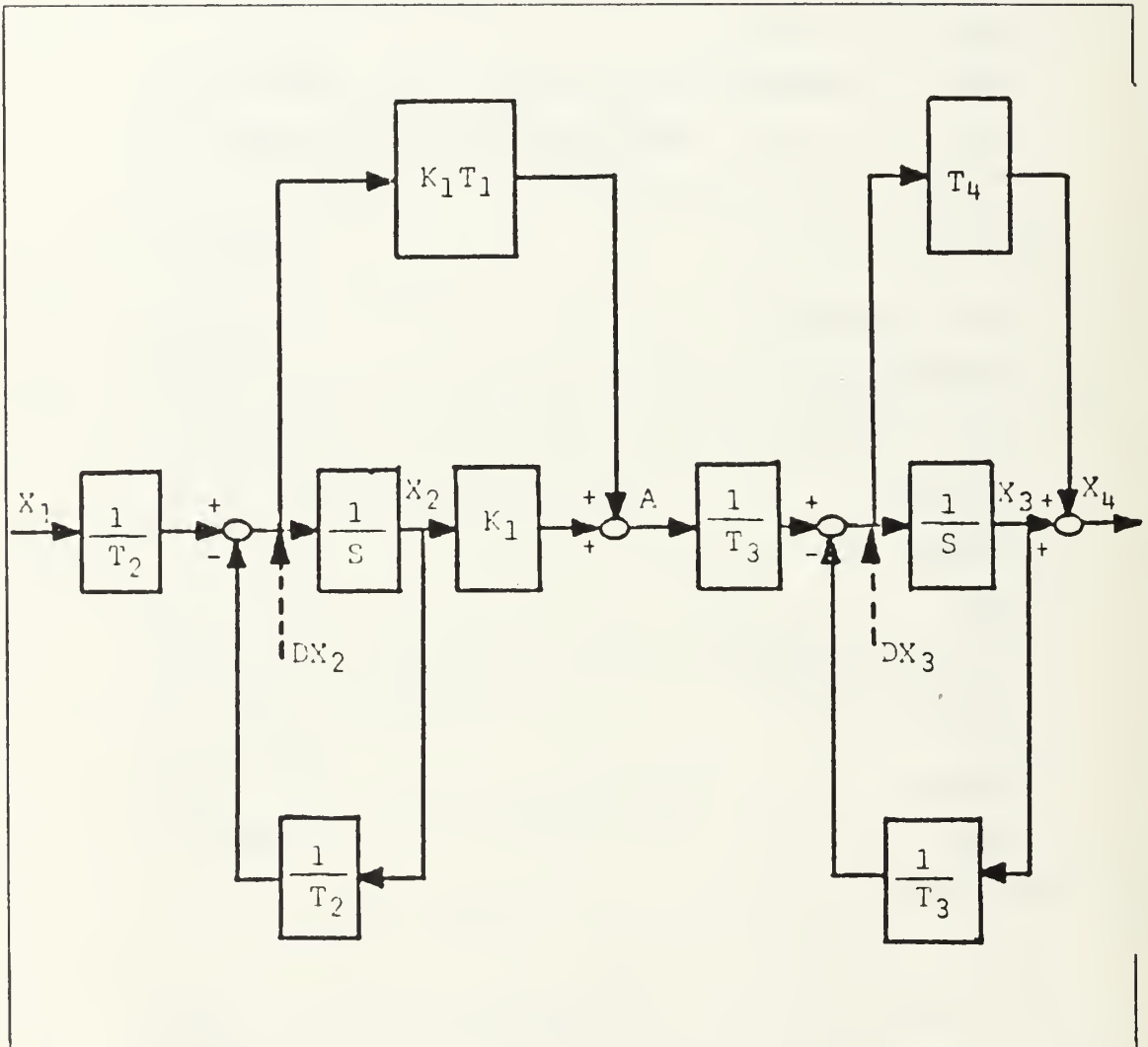


Figure B.1 Block Diagram of Controller C

Figure B.1 corresponds to controller 'C' which has the form:

$$\frac{K_1(1+T_1S)(1+T_4S)}{(1+T_2S)(1+T_3S)} \quad (\text{B.1})$$

Verifying that equation B.1 corresponds to controller 'C' we have:

$$A = \frac{X_1 K_1}{1+T_2S} + K_1 T_1 D X_2 \quad (\text{B.2})$$

$$\frac{X_2}{DX_2} = \frac{1}{S} \quad DX_2 = S X_2 \quad (\text{B.3})$$

$$\frac{X_2}{X_1} = \frac{1}{1+T_2S} \quad X_2 = \frac{X_1}{1+T_2S} \quad (\text{B.4})$$

Substituting equations B.3 , B.4 into equation B.2 we have:

$$A = \frac{X_1 K_1}{1+T_2S} + \frac{K_1 T_1 X_1 S}{1+T_2S} \quad (\text{B.5})$$

We also have:

$$X_4 = \frac{A}{1+T_3S} + T_4 D X_3 \quad (\text{B.6})$$

$$\frac{X_3}{DX_3} = \frac{1}{S} \quad DX_3 = X_3 S \quad (\text{B.7})$$

$$\frac{X_3}{A} = \frac{1}{1+T_3S} \quad X_3 = \frac{A}{1+T_3S} \quad (\text{B.8})$$

Substituting equations B.7 , B.8 into equation B.6 we have:

$$X_4 = \frac{A}{1+T_3S} + \frac{T_4AS}{1+T_3S} \quad (\text{B.9})$$

Now substituting equation B.5 into equation B.9 we have:

$$X = \frac{X_1K_1}{(1+T_2S)(1+T_3S)} + \frac{X_1K_1T_1S}{(1+T_2S)(1+T_3S)} + \frac{X_1K_1T_4S}{(1+T_2S)(1+T_3S)} + \frac{X_1K_1T_1T_4S^2}{(1+T_2S)(1+T_3S)} \quad (\text{B.10})$$

Finally rearranging terms equation B.10 can be written:

$$\frac{X_4}{X_1} = \frac{K_1(1+T_1S+T_4S+T_1T_4S^2)}{(1+T_2S)(1+T_3S)} = \frac{K_1(1+T_1S)(1+T_4S)}{(1+T_2S)(1+T_3S)} \quad (\text{B.11})$$

B. CONTROLLER "B"

Figure B.2 corresponds to controller 'B' which has the form:

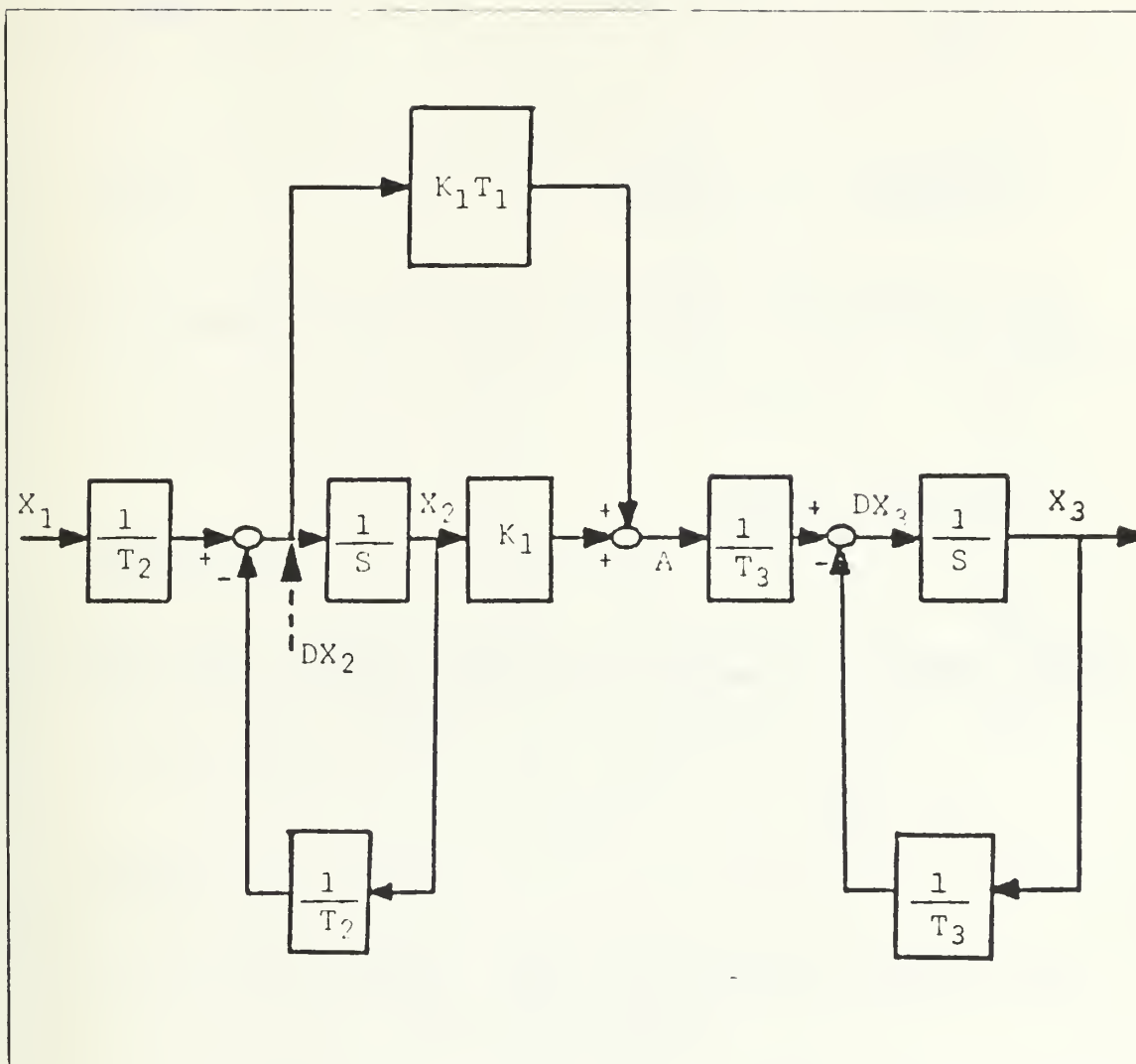


Figure B.2 Block Diagram of Controller B

$$\frac{K_1(1+T_1S)}{(1+T_2S)(1+T_3S)} \quad (B.12)$$

Verifying that equation B.12 corresponds to Controller 'B' we have:

$$A = \frac{K_1 X_1}{1+T_2S} + K_1 T_1 DX_2 \quad (B.13)$$

$$\frac{X_2}{DX_2} = \frac{1}{S} \quad DX_2 = X_2 S \quad (B.14)$$

$$\frac{X_2}{X_1} = \frac{1}{T_2 S + 1} \quad X_2 = \frac{X_1}{1 + T_2 S} \quad (B.15)$$

Substituting equations B.14 , B.15 into equation B.13 we have:

$$A = \frac{K_1 X_1}{1 + T_2 S} + \frac{K_1 T_1 X_1 S}{1 + T_2 S} \quad (B.16)$$

In a similar way we also can derive equation B.17

$$X_3 = \frac{A}{1 + T_3 S} \quad (B.17)$$

Substituting equation B.16 into equation B.17 we have:

$$X_3 = \frac{K_1 X_1}{(1 + T_2 S)(1 + T_3 S)} + \frac{K_1 T_1 X_1 S}{(1 + T_2 S)(1 + T_3 S)} \quad (B.18)$$

Finally rearranging terms equation B.18 becomes:

$$\frac{X_3}{X_1} = \frac{K_1(1 + T_1 S)}{(1 + T_2 S)(1 + T_3 S)} \quad (B.19)$$

C. CONTROLLER "A"

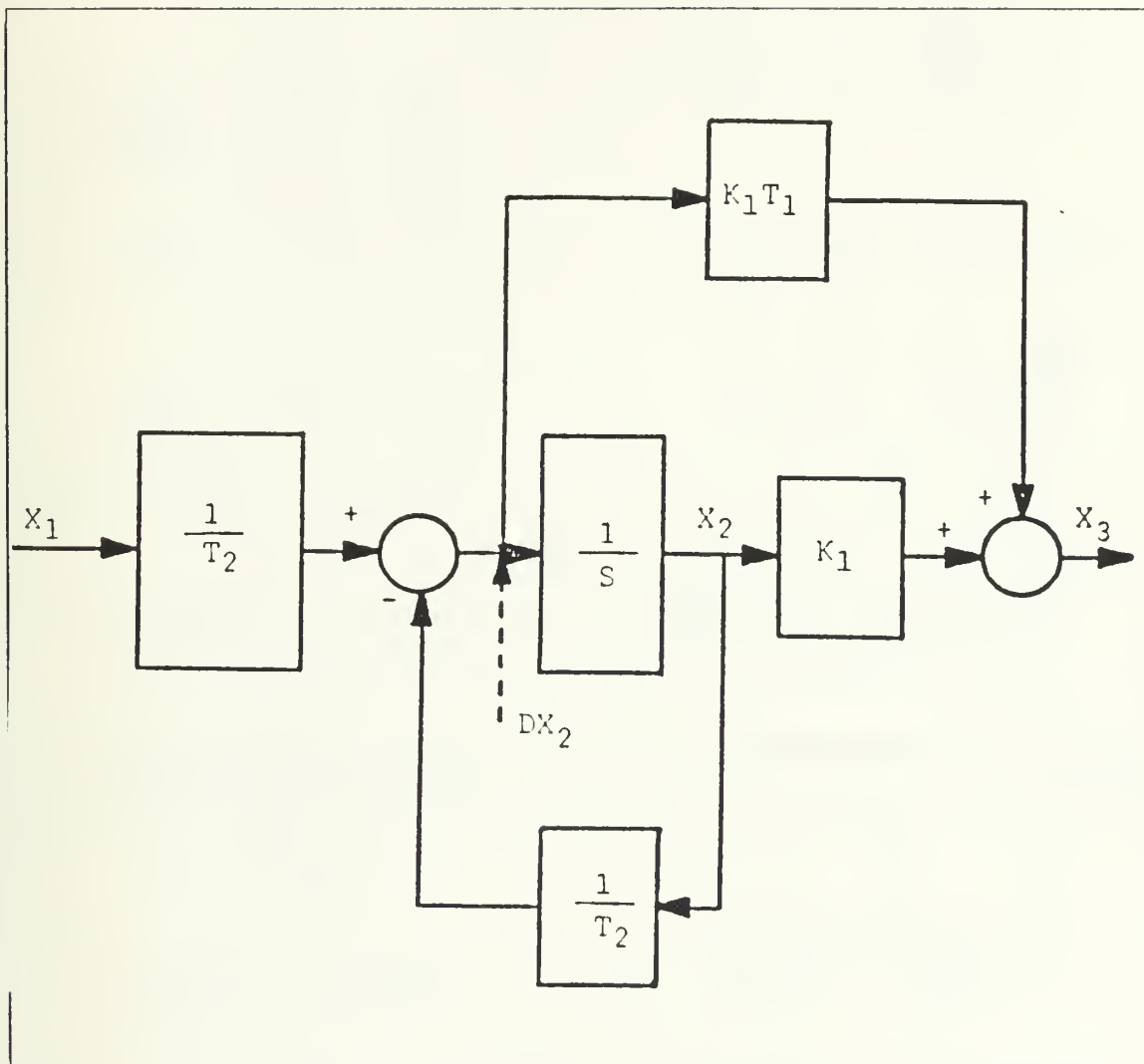


Figure B.3 Block Diagram of Controller A

Figure B.3 corresponds to controller 'A' which has the form:

$$\frac{K_1(1+T_1S)}{1+T_2S}$$

(B.20)

Verifying that equation B.20 corresponds to Controller 'A' we have:

$$X_3 = \frac{X_1 K_1}{1+T_2 S} + K_1 T_1 D X_2 \quad (B.21)$$

But since we know that:

$$\frac{D X_2}{X_2} = \frac{1}{S} \quad D X_2 = X_2 S \quad (B.22)$$

$$\frac{X_2}{X_1} = \frac{1}{1+T_2 S} \quad X_2 = \frac{X_1}{1+T_2 S} \quad (B.23)$$

Substituting equation B.22 , B.23 into equation B.21 we have:

$$X_3 = \frac{X_1 K_1}{1+T_2 S} + \frac{K_1 T_1 X_1 S}{1+T_2 S} \quad (B.24)$$

Finally rearranging terms equation B.24 becomes:

$$\frac{X_3}{X_1} = \frac{K_1 (1+T_1 S)}{1+T_2 S} \quad (B.25)$$

D. CODING OF THE EQUATIONS

-----For Controller "C"-----Integration-----

$$YAW_E = YAW_C - YAW$$

$$YAW_E = YAW - YAW_C$$

$$DX_2 = \frac{(YAW_E - X_2)}{T_2}$$

$$A = K_1(X_2 + T_1 DX_2)$$

$$DX_3 = \frac{A - X_3}{T_3}$$

$$D = X_3 + T_4 DX_3$$

$$X_2 = X_2 + DX_2 \cdot \text{DELT}$$

$$X_3 = X_3 + DX_3 \cdot \text{DELT}$$

-----For Controller "B"-----Integration-----

$$YAW_E = YAW - YAW_C$$

$$DX_2 = \frac{YAW_E - X_2}{T_2}$$

$$A = K_1(X_2 + T_1 DX_2)$$

$$D = X_3$$

$$\dot{X}_2 = X_2 + DX_2 \cdot \text{DELT}$$

$$X_3 = X_3 + DX_3 \cdot \text{DELT}$$

-----For Controller "A"-----Integration-----

$$YAW_E = YAW - YAW_C$$

$$DX_2 = \frac{YAW_E - X_2}{T_2}$$

$$D = K_1(X_2 + T_1 DX_2)$$

$$X_2 = X_2 + DX_2 \cdot \text{DELT}$$

For all of the above cases the equations include the error detector and the controller which are indicated in Figure B.4

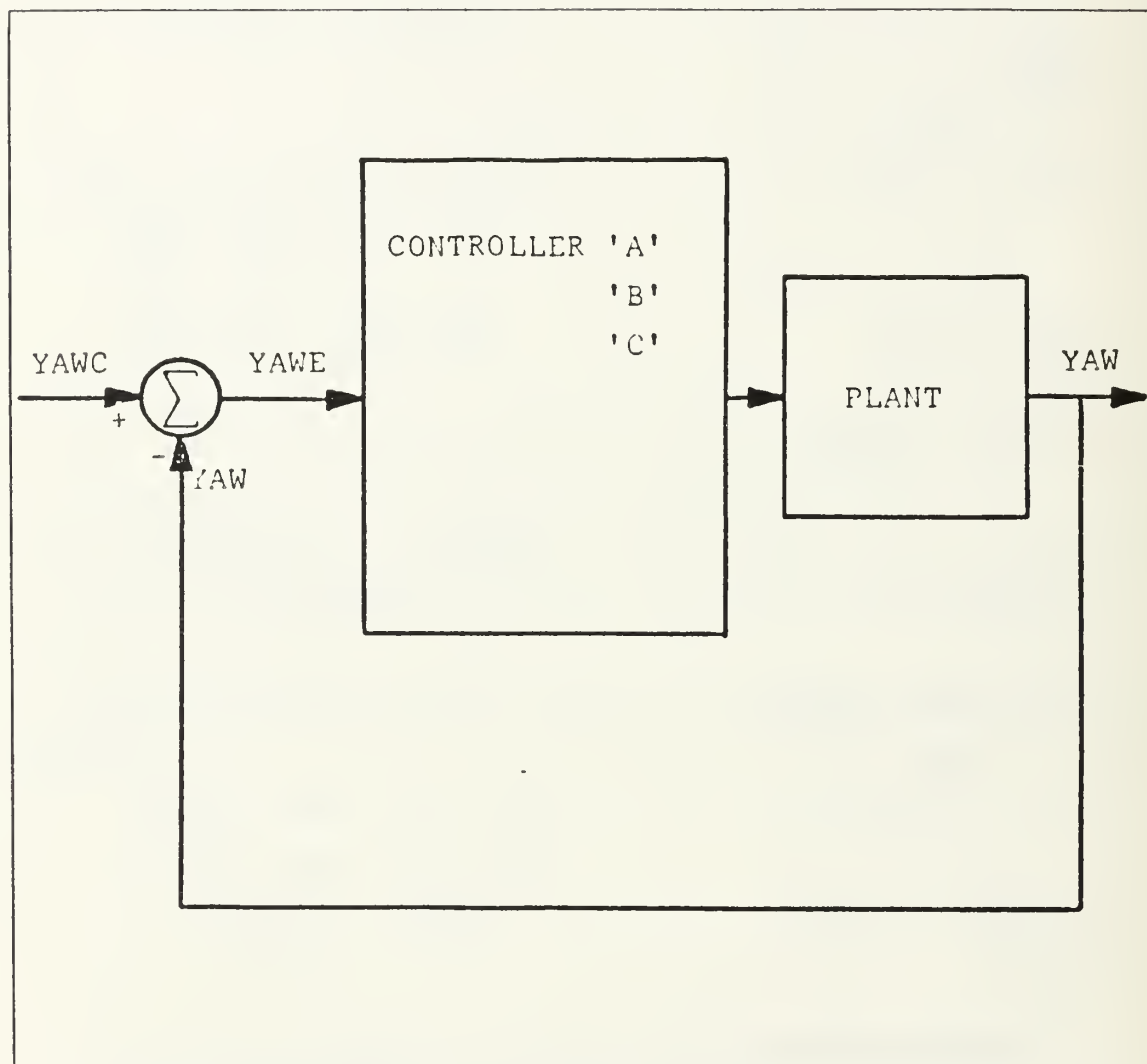


Figure B.4 General Scheme of Control

APPENDIX C

RESPONSE OF THE SYSTEM FOR REGULAR SEAS

```
//PROGRA JOB (????,0356),'RESEARCH',CLASS=A
//*MAIN ORG=NPGVM1.????P
// EXEC FORTXCG,PARM.FORT='OPT(2)',IMSL=DP,REGION=1024K
//FORT.SYSIN DD *
C
C
C IN ORDER TO PERFORM SIMULATION ONLY WHEN GAINS
C HAVE BEEN OBTAINED CHANGE XS(*) TO X(*) AND DELETE
c XU(*),AND XL(*).
      COMMON J
      DIMENSION X(5)
      X(1)=1.8287125
      X(2)=1.1652012
      X(3)=10.5659571
      X(4)=11.7124157
      X(5)=20.5683947
C  CALL PLANT(X)
C  IF ONLY SIMULATION IS WANTED
      CALL PLANT(X)
      WRITE (6,25)
25  FORMAT(1X,' OPTIMAL GAINS',/)
      DO 30 I=1,5
30  WRITE(6,40)I,X(I)
40  FORMAT(1X,'X(',I2,')=' ,F14.7)
      WRITE(6,50) J
50  FORMAT(1X,'J = ',E15.10)
      STOP
      END
      SUBROUTINE PLANT(XX)
C  SUBROUTINE PLANT(XX) SIMULATES THE SHIP
```

```

COMMON TDIFF
REAL*8 L,L2,L3,L4,L5,L6
REAL*8 X,XDOT,Y,YDOT,U,UDOT,V,VDOT,YAW,R,RDOT
REAL*8 TIME,ETIME,XUDOT,XUU,XVR,XVV,XDD
REAL*8 YV,YR,YD,YVVR,YVRR,YVVV,YRRR,YDDD,YVDOT
REAL*8 NV,NR,ND,NVVR,NVRR,NVVV,NRRR,NDDD,NRDOT
REAL*8 RHO,IZ,FX,FY,MZ,XP,MASS,DELT,MZI,RXI,WA,WE
REAL*8 DYAW,YAW,YAWC,ISE,ISR,LAMDA,D,RYR,RYI,MZR
REAL*8 K1,T1,T2,D,X2,DX2,S,RX,RY,RZ,TX,TY,TZ,RXR
REAL*8 T3,T4,X3,DX3,X4
DIMENSION XX(5)

C
C CLOSE LOOP ANALYSIS WITH FILTER
C
C INITIAL CONDITIONS FOR INTEGRATION
C SIMULATION END TIME IN SECONDS
    ETIME=600.
    TIME=0.0
    ICOUNT=1.0
C INITIALIZE THE COST FUNCTION
    ISE=0.0
    ISR=0.0
    TDIFF=0.0
    LAMDA=8.128
C GAIN COEFFICIENTS TO BE OPTIMIZED
    K1=XX(1)
    T1=XX(2)
    T2=XX(3)
    T3=XX(4)
    T4=XX(5)
C WRITE(6,1010) K1,T1,T2
C1010 FORMAT(1X,'K1 =',F15.7,'T1 =',F15.7,'T2 =',F15.7)
C X,XDOT,Y,YDOT ARE FIX COORDINATES ON EARTH
    X=0.0
    Y=0.0

```

```

      XDOT=0.0
      YDOT=0.0
C   U,UDOT,V,VDOT ARE FIX COORDINATES ON SHIP
      V=0.0
      UDOT=0.0
      VDOT=0.0
      YAW=0.0
      R=0.0
      RDOT=0.0
C   ORDERED SPEED IN FEET/SEC
C   38.82 FT/SEC=23 KNOTS
      UC=38.82
C   AT STEADY STATE ACTUAL SPEED (U) = COMMAND SPEED (UC)
      U=UC
C   D = RUDDER ANGLE
      D=0.0
      L=880.5
      L2=L**2
      L3=L*L*L
      L4=L*L3
      L5=L*L4
      L6=L*L5
C   SEA DISTURBANCE
C   FORCES IN X,Y DIRECTION COMPUTED IN FORCES
C   MOMENTS IN Z
      FX=0.
      FY=0.
      MZ=0.
C   RXR=-0.15744D+05
C   RXI=-0.19950D+06
C   RYR=0.52365D+04
C   RYI=0.18699D+06
C   MZR=-0.29870D+08
C   MZI=-0.35751D+07
C   RXR=-0.50230D+04

```

```

C      RXI=0.12712D+05
C      RYR=0.35290D+04
C      RYI=-0.31909D+05
C      MZR=0.38826D+07
C      MZI=-0.64313D+07
      RXR=0.28540D+04
      RXI=-0.99574D+04
      RYR=-0.85441D+04
      RYI=0.39595D+05
      MZR=-0.13014D+08
      MZI=0.11348D+08
C      RXR=-0.75642D+04
C      RXI=0.83497D+04
C      RYR=0.23379D+05
C      RYI=-0.81502D+05
C      MZR=0.28622D+07
C      MZI=-0.19388D+08
C      RXR=-0.37916D+04
C      RXI=0.16381D+04
C      RYR=-0.76647D+05
C      RYI=-0.37685D+05
C      MZR=-0.83915D+07
C      MZI=-0.53176D+07
      RX=DSQRT(RXR**2+RXI**2)
      RY=DSQRT(RYR**2+RYI**2)
      RZ=DSQRT(MZR**2+MZI**2)
      TX=DATAN(RXI/RXR)
      TY=DATAN(RYI/RYR)
      TZ=DATAN(MZI/MZR)
C  SIGNIFICANT WAVE HEIGHT; SEA STATE 1-5,2-10,3-15,
C  4-17.5,5-22.5 6-27,7-35,8-42,9-60
      WA=17.5
C  ENCOUNTER FREQUENCY .1,.2,.3,.4,.5,.6,.75,1.0,1.5,2.5
      WE=0.6
C  HYDRODYNAMIC COEFFICIENTS ARE INSERTED HERE

```

```

C  AS PARAMETERS
    RHO=1.9876
    MASS=(.0044)*(.5*RHO*L3)
    IZ=(0.00028)*(.5*RHO*L5)
    YAW=0.0
    X2=0.0
    DX2=0.0
    X3=0.0
    DX3=0.0
    X4=0.0
200 CONTINUE
    S=DSQRT(U**2+V**2)
C  INPUT YAW COMMAND
    YAWC=0.0
    IF (TIME.GE.0.0) YAWC=0.0
C  ERROR SIGNAL TO DRIVE RUDDER(YAW ACTUAL-YAW ORDERED)
C  ( COMPENSATOR FILTER )
    YAWE=YAW - YAWC
    DX2=(YAWE-X2)/T2
    X4=K1*(T1*DX2+X2)
    DX3=(X4-X3)/T4
    D=(T3*DX3+X4)
C  AXIAL FORCE HYDRODYNAMIC COEFFICIENTS (SURGE)
C  XUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED
C  FOR DIFFERENT ENCOUNTER ANGLE , SPEED , ENCOUNTER
C  FREQUENCY
    XUDOT=(-.0001)*(.5*RHO*L3)
    XU=(-0.0253)*(.5*RHO*L2*S)
    XU=U*(-0.0003)*(.5*RHO*L2)
    XVR=(0.0039)*(.5*RHO*L3)
    XVV=(-.0012)*(.5*RHO*L2)
    XDD=(-0.0005)*(.5*RHO*L2*S**2)
C  LATERAL FORCE HYDRODYNAMIC COEFFICIENTS (SWAY)
C  YV=(-0.00758)*(.5*RHO*L2*S)
    YR=(0.0023)*(.5*RHO*L3*S)

```



```

YD=(0.00145)*(.5*RHO*L2*S**2)
YVVR=(0.01)*(.5*RHO*L3/S)
YVRR=(-0.008)*(.5*RHO*L4/S)
YVVV=(-0.03)*(.5*RHO*L2/S)
YRRR=(0.003)*(.5*RHO*L5/S)
YDDD=(-0.0005)*(.5*RHO*L2*S**2)
C  YUDOT IS THE ADDED MASS TERM WHICH MUST BE
C  CHANGED FOR DIFFERENT ENCOUNTER ANGLE , SPEED ,
C  ENCOUNTER FREQUENCY
C      YVDOT=(-0.0039)*(.5*RHO*L3)
C  SPEED=23 KNOTS, ENCOUNTER ANGLE = 30 , ENCOUNTER
c  FREQUENCY =0.4
C      YVDOT=-0.30908D+07
C      YV=-0.81271D+04
C      YVDOT=-0.36185D+07
C      YV=-0.24757D+06
      YVDOT=-0.32890D+07
      YV=-0.11775D+07
C      YVDOT=-0.23038D+07
C      YV=-0.18267D+07
C      YVDOT=-0.59800D+06
C      YV=-0.13260D+07
C  MOMENT ABOUT Z-AXIS HYDRODYNAMIC COEFFICIENTS (YAW)
      NV=(-0.00213)*(.5*RHO*L3*S)
C      NR=(-0.00105)*(.5*RHO*L4*S)
      ND=(-0.0007)*(.5*RHO*L3*S**2)
      NVVR=(-0.015)*(.5*RHO*L4/S)
      NVRR=(-0.008)*(.5*RHO*L5/S)
      NVVV=(0.01)*(.5*RHO*L3/S)
      NRRR=(-0.006)*(.5*RHO*L6/S)
      NDDD=(0.0001)*(.5*RHO*L3*S**2)
C  NRDOT IS THE ADDED INERTIA TERM WHICH MUST BE CHANGED
C  FOR DIFFERENT ENCOUNTER ANGLE , SPEED , ENCOUNTER
C  FREQUENCY
C      NRDOT=(-0.00027)*(.5*RHO*L5)

```

```

C  SPEED=23 KNOTS, ENCOUNTER ANGLE = 30 , ENCOUNTER
C  FREQUENCY =0.4
C      NRDOT=-0.26251D+12
C      NR=-0.53637D+09
C      NRDOT=-0.20125D+12
C      NR=-0.94970D+10
C      NRDOT=-0.18671D+12
C      NR=-0.46860D+11
C      NRDOT=-0.14518D+12
C      NR=-0.87538D+11
C      NRDOT=-0.37261D+11
C      NR=-0.69856D+11
C  REGULAR WAVE SEA STATE
C      FX=WA*RX*DCOS(WE*TIME+TX)
C      FY=WA*RY*DCOS(WE*TIME+TY)
C      MZ=WA*RZ*DCOS(WE*TIME+TZ)
C  U ACTUAL SPEED
C  UC COMMANDED SPEED
C  XP = PROPELLER THRUST
C      XP=-XUU*UC**2
C  EQUATIONS OF MOTION
C      UDOT=( (XVR + MASS)*V*R + XUU*U**2 + XVV*V**2
C      1 + XDD*D*D + FX + XP )/(MASS-XUDOT)
C      VDOT=(YV*V + (YR-MASS*U)*R + YD*D
C      1 + YVVR*V**2*R + YVRR*V*R**2
C      1 + YVVV*V**3 + YRRR*R**3 + YDDD*D**3
C      1 + FY )/(MASS-YVDOT)
C      RDOT=( NV*V + NR*R + ND*D + NVVR*V**2*R
C      1 + NVRR*V*R**2
C      1 + NVVV*V**3 + NRRR*R**3 + NDDD*D**3
C      1 + MZ )/(iz-NRDOT)
C  WHEN TO PRINTOUT
C      IF (ICOUNT.EQ. 2) GO TO 50
C      GO TO 300
C  CONVERT RADIANS TO DEGREES

```

```

50  YAWDEG= YAW*57.296
    RDEG=R*57.296
    RDDEG=RDOT*57.296
    DDEG=D*57.296
    YAWC=YAWC*57.296
    WRITE (6,100) TIME,YAWDEG
C    1  ,UC,U,UDOT,V,VDOT,YAWC,YAWDEG,RDEG,RDDEG,DDEG
100  FORMAT(1X,F12.8,1X,F12.8)
C    1' FT  XDOT=',F8.4,' FT/SEC  Y=',F8.2,' FT
C    1  YDOT=',F8.4,' FT/SEC
C    1' ,/,2X,' UC=',F8.4,' FT/SEC  U=',F8.4,'
C    1 FT/SEC  UDOT=',F10.6,
C    1 ' FT/SEC**2  V=',F8.4,' FT/SEC
C    1 VDOT=',F10.6,' FT/SEC**2'
C    1 ,/,2X,'YAWC=',F8.4,' DEG  YAW='
C    1  ,F15.7,' DEG  YAW RATE=',F15.7,'
C    1 DEG/SEC  YAW ACCEL='
C    1 ,F15.7,' DEG/SEC**2',/,2X,'
C    1 RUDDER =',F15.7,' DEG ')
C    WRITE (6,101) TIME,DDEG
C101  FORMAT(1X,F12.8,1X,F12.8)
    ICOUNT=1
C    TEST IF WANT TO STOP
    300  IF (TIME.GE.ETIME) GO TO 400
C    INTEGRATION STEP SIZE DELT
    DELT=1.0
C    INTEGRATION
    U=U+UDOT*DELT
    V=V+VDOT*DELT
    R=R+RDOT*DELT
    YAW=YAW+R*DELT
    X2=X2+DX2*DELT
    X3=X3+DX3*DELT
C    CONVERT SHIP TO FIXED COORDINATES ON EARTH
    XDOT=U*DCOS(YAW)-V*DSIN(YAW)

```

```

YDOT=U*DSIN(YAW)+V*DCOS(YAW)
X=X+XDOT*DELT
Y=Y+YDOT*DELT
TIME=TIME+DELT
ICOUNT=ICOUNT+1
ISE=ISE + LAMDA*YAW**2
ISR=ISR + D**2
GO TO 200
C J=TDIFF= COST FUNCTION
400 TDIFF=ISE+ISR
WRITE(6,500) ISE,ISR,TDIFF,K1,T1,T2,T3,T4
500 FORMAT(' ',1X,'ISE=',F15.7,' ISR=',F15.7,'
1 TOTAL=',F15.7,2X,
1 'K1=',F15.7,2X,'T1=',F15.7,2X,'T2=',F15.7,2X,
1 'T3=',F15.7,2X,'T4=',F15.7)
RETURN
END
//GO.SYSIN DD *
/*

```

APPENDIX D

DETERMINATION OF OPTIMAL CONTROLLER PARAMETERS FOR IRREGULAR SEAS

```
//TRIAL1 JOB (1707,0356),'RESEARCH',CLASS=C
//*MAIN ORG=NPGVM1.1707P
// EXEC FORTXCG,PARM.FORT='OPT(2)',IMSL=DP,REGION=1024K
//FORT.SYSIN DD *
C  THIS PROGRAM WILL OBTAIN THE CONTROLLER OPTIMAL
C  GAINS. IT IS REFERENCED IN CHAPTER 5.
C  IN ORDER TO PERFORM SIMULATION ONLY WHEN GAINS
C  HAVE BEEN OBTAINED CHANGE XS(*) TO X(*) AND
C  DELETE XU(*),AND XL(*).
      DIMENSION XS(5),XU(5),XL(5)
      XS(1)=0.655751
      XS(2)=80.5483
      XS(3)=10.74847
      XS(4)=12.9
      XS(5)=45.09
C  XS(I) IS THE STARTING GUESS
C  XL(I) IS THE LOWER LIMIT FOR THE I'TH VARIABLE
C  XU(I) IS THE UPPER LIMIT FOR THE I'TH VARIABLE
      XL(1)=0.1
      XU(1)=2.5
      XL(2)=40.0
      XU(2)=100.0
      XL(3)=0.1
      XU(3)=20.0
      XL(4)=5.0
      XU(4)=80.0
      XL(5)=60.0
      XU(5)=150.0
C  A DESCRIPTION OF THE FOLLOWING PARAMETERS
```

```

C   IS DISCUSSED IN BOXPLX
      R=9./13.
      NTA=1000
      NPR=100
      NAV=0
      NV=5
      IP=0

C   THE FOLLOWING STATEMENT MUST BE CHANGED TO
C   CALL PLANT(X)
C   IF ONLY SIMULATION IS WANTED
      CALL BOXPLX(NV,NAV,NPR,NTA,R,XS,IP,XU,XL,YMN,IER)
      WRITE (6,25)
25    FORMAT(1X,' OPTIMAL GAINS ',/)
      DO 30 I=1,5
30    WRITE(6,40)I,XS(I)
40    FORMAT(1X,'X(',I2,')=' ,F14.7)
      STOP
      END
      SUBROUTINE PLANT(XX)

C   SUBROUTINE PLANT(XX) SIMULATES THE SHIP
      COMMON TDIFF
      REAL*8 L,L2,L3,L4,L5,L6
      REAL*8 X,XDOT,Y,YDOT,U,UDOT,V,VDOT,YAW,R,RDOT
      REAL*8 TIME,ETIME,XUDOT,XUU,XVR,XVV,XDD
      REAL*8 YV,YR,YD,YVVR,YVRR,YVVV,YRRR,YDDD,YVDOT
      REAL*8 NV,NR,ND,NVVR,NVRR,NVVV,NRRR,NDDD,NRDOT
      REAL*8 RHO,IZ,FX,FY,MZ,XP,MASS,DELT
      REAL*8 DYAW,YAW,YAWC,ISE,ISR,LAMDA,D
      REAL*8 K1,T1,T2,T3,T4,D,X2,DX2,X3,DX3,X4,CH(11),S
      DIMENSION XX(5)

C
C   CLOSE LOOP ANALYSIS WITH FILTER
C
C   INITIAL CONDITIONS FOR INTEGRATION
C   SIMULATION END TIME IN SECONDS

```

```

        ETIME=600.
        TIME=0.0
        ICOUNT=1
C   INITIALIZE THE COST FUNCTION
        ISE=0.0
        ISR=0.0
        TDIFF=0.0
        LAMDA=8.128
C   GAIN COEFFICIENTS TO BE OPTIMIZED
        K1=XX(1)
        T1=XX(2)
        T2=XX(3)
        T3=XX(4)
        T4=XX(5)
C       WRITE(6,1010) K1,T1,T2
C1010  FORMAT(1X,'K1 =',F15.7,' T1 =',F15.7,'
C      1  T2=',F15.7  )
C   X,XDOT,Y,YDOT ARE FIX COORDINATES ON EARTH
        X=0.0
        Y=0.0
        XDOT=0.0
        YDOT=0.0
C   U,UDOT,V,VDOT ARE FIX COORDINATES ON SHIP
        V=0.0
        UDOT=0.0
        VDOT=0.0
        YAW=0.0
        R=0.0
        RDOT=0.0
C   ORDERED SPEED IN FEET/SEC
C   38.82 FT/SEC=23 KNOTS
        UC=38.82
C   AT STEADY STATE ACTUAL SPEED (U) = COMMAND SPEED (UC)
        U=UC
C   D = RUDDER ANGLE

```

```

D=0.0
L=880.5
L2=L**2
L3=L*L*L
L4=L*L3
L5=L*L4
L6=L*L5
C  SEA DISTURBANCE
C  FORCES IN X,Y DIRECTION COMPUTED IN FORCES
C  MOMENTS IN Z
    FX=0.
    FY=0.
    MZ=0.
C  ISEA IS A SWITCH;ISEA=0 (CALM WATER) ISEA=1 (SEA STATE)
    ISEA=1
C  HYDRODYNAMIC COEFFICIENTS ARE INSERTED HERE AS
C  PARAMETERS
    RHO=1.9876
    MASS=(.0044)*(.5*RHO*L3)
    IZ=(0.00028)*(.5*RHO*L5)
    YAWE=0.0
    X2=0.0
    DX2=0.0
    X3=0.0
    DX3=0.0
    X4=0.0
200 CONTINUE
    S=DSQRT(U**2+V**2)
C  INPUT YAW COMMAND
    YAWC=0.0
    IF (TIME.GE.0.0) YAWC=0.0
C  ERROR SIGNAL TO DRIVE RUDDER(YAW ACTUAL-YAW ORDERED)
C  ( CONTROLLER  FILTER )
    YAWE=YAW - YAWC
    DX2=(YAWE-X2)/T2

```



```

X4=K1*(T1*DX2+X2)
DX3=(X4-X3)/T4
D=(T3*DX3+X4)
C  AXIAL FORCE HYDRODYNAMIC COEFFICIENTS (SURGE)
C  XUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED
C  FOR DIFFERENT ENCOUNTER ANGLE , SPEED , ENCOUNTER
C  FREQUENCY
      XUDOT=(-.0001)*(.5*RHO*L3)
      XU=(-0.0253)*(.5*RHO*L2*S)
      XUU=(-0.0003)*(.5*RHO*L2)
      XVR=(0.0039)*(.5*RHO*L3)
      XVV=(-.0012)*(.5*RHO*L2)
      XDD=(-0.0005)*(.5*RHO*L2*S**2)
C  LATERAL FORCE HYDRODYNAMIC COEFFICIENTS (SWAY)
      YV=(-0.00758)*(.5*RHO*L2*S)
      YR=(0.0023)*(.5*RHO*L3*S)
      YD=(0.00145)*(.5*RHO*L2*S**2)
      YVVR=(0.01)*(.5*RHO*L3/S)
      YVRR=(-0.008)*(.5*RHO*L4/S)
      YVVV=(-0.03)*(.5*RHO*L2/S)
      YRRR=(0.003)*(.5*RHO*L5/S)
      YDDD=(-0.0005)*(.5*RHO*L2*S**2)
C  YUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED
C  FOR DIFFERENT ENCOUNTER ANGLE , SPEED , ENCOUNTER
C  FREQUENCY
      YVDOT=(-0.0039)*(.5*RHO*L3)
C  SPEED=23 KNOTS, ENCOUNTER ANGLE =      ,
C  ENCOUNTER FREQUENCY =.75
      YVDOT=-2304300.0
C  MOMENT ABOUT Z-AXIS HYDRODYNAMIC COEFFICIENTS (YAW)
      NV=(-0.00213)*(.5*RHO*L3*S)
      NR=(-0.00105)*(.5*RHO*L4*S)
      ND=(-0.0007)*(.5*RHO*L3*S**2)
      NVVR=(-0.015)*(.5*RHO*L4/S)
      NVRR=(-0.008)*(.5*RHO*L5/S)

```

```

      NVVV=(0.01)*(.5*RHO*L3/S)
      NRRR=(-0.006)*(.5*RHO*L6/S)
      NDDD=(0.0001)*(.5*RHO*L3*S**2)
C   NRDOT IS THE ADDED INERTIA TERM WHICH MUST BE
C   CHANGED FOR DIFFERENT ENCOUNTER ANGLE , SPEED ,
C   ENCOUNTER FREQUENCY
C      NRDOT=(-0.00027)*(.5*RHO*L5)
C   SPEED=23 KNOTS, ENCOUNTER ANGLE =      ,
C   ENCOUNTER FREQUENCY =.75
      NRDOT=-1.4518E+11
C   SETS SEA STATE TO ZERO
      IF (ISEA.EQ.1) GO TO 30
      FX=0.
      FY=0.
      MZ=0.
      GO TO 35
C   UNIT 12 HAS THE SEA STATE DATA NAMED CH
C   IT MUST BE SYNCHRONIZED BY TIME
30   READ (12) CH
      FX=CH(3)
      FY=CH(4)
      MZ=CH(8)
35   CONTINUE
C   U ACTUAL SPEED
C   UC COMMANDED SPEED
C   XP = PROPELLER THRUST
      XP=-XUU*UC**2
C   EQUATIONS OF MOTION
C      UDOT=( (XVR + MASS)*V*R + XUU*U**2 + XVV*V**2
C      1 + XDD*D*D + FX + XP )/(MASS-XUDOT)
      VDOT=(YV*V + (YR-MASS*U)*R + YD*D + YVVR*V**2*R
      1 + YVRR*V*R**2
      1 + YVVV*V**3 + YRRR*R**3 + YDDD*D**3
      1 + FY )/(MASS-YVDOT)
      RDOT=( NV*V + NR*R + ND*D + NVVR*V**2*R

```

```

      1 + NVRR*V*R**2
      1 + NVVV*V**3 + NRRR*R**3 + NDDD*D**3
      1 + MZ )/(IZ-NRDOT)
C   WHEN TO PRINTOUT
      IF (ICOUNT.EQ.11) GO TO 50
      GO TO 300
C   CONVERT RADIANS TO DEGREES
50   YAWDEG= YAW*57.296
      RDEG=R*57.296
      RDDEG=RDOT*57.296
      DDEG=D*57.296
      YAWC=YAWC*57.296
C   WRITE (6,100) TIME,XP,X,XDOT,Y,YDOT
C   1   ,UC,U,UDOT,V,VDOT,YAWC,YAWDEG,RDEG,RDDEG,DDEG
100  FORMAT(1X,'TIME=',F8.3,' SEC  XP=',F10.2,' LBF
      1  X=',F8.2,
      1' FT  XDOT=',F8.4,' FT/SEC  Y=',F8.2,' FT  YDOT='
      1 ,F8.4,' FT/SEC
      1' ,/,2X,' UC=',F8.4,' FT/SEC  U=',F8.4,' FT/SEC
      1 UDOT=',F10.6,
      1 ' FT/SEC**2  V=',F8.4,' FT/SEC  VDOT=',F10.6,
      1 ' FT/SEC**2',/,2X,'YAWC=',F8.4,' DEG  YAW='
      1 ,F15.7,' DEG  YAW RATE=',F15.7,' DEG/SEC
      1  YAW ACCEL='
      1 ,F15.7,' DEG/SEC**2',/,2X,'RUDDER =',F15.7,'
      1 DEG ',/)
      ICOUNT=1
C   TEST IF WANT TO STOP
300  IF (TIME.GE.ETIME) GO TO 400
C   INTEGRATION STEP SIZE DELT
      DELT=1.0
C   INTEGRATION
      U=U+UDOT*DELT
      V=V+VDOT*DELT
      R=R+RDOT*DELT

```

```

        YAW=YAW+R*DELT
        X2=X2+DX2*DELT
        X3=X3+DX3*DELT
C   CONVERT SHIP TO FIXED COORDINATES ON EARTH
C       XDOT=U*DCOS(YAW)-V*DSIN(YAW)
C       YDOT=U*DSIN(YAW)+V*DCOS(YAW)
C       X=X+XDOT*DELT
C       Y=Y+YDOT*DELT
        TIME=TIME+DELT
        ICOUNT=ICOUNT+1
        ISE=ISE + LAMDA*YAW**2
        ISR=ISR + D**2
        GO TO 200
C   J=TDIFF= COST FUNCTION
400   TDIFF=ISE+ISR
        WRITE(6,500) TDIFF,K1,T1,T2,T3,T4
500   FORMAT(' ',1X,'TDIFF =',F15.7,' K1 =',F15.7,'
1   T1 =',F15.7,2X,
1   'T2=',F15.7,2X,'T3=',F15.7,2X,'T4=',F15.7)
        REWIND 12
        RETURN
        END
C   BETWEEN LINE 249(END) AND THE FOLLOWING LINE
C   (//GO.SYSIN DD *)WE HAVE TO INCLUDE BOXPLX.
//GO.SYSIN DD *
/*
//GO.FT12F001 DD DISP=SHR,DSN=MSS.S2160.A213

```

APPENDIX E

RESPONSE OF THE SYSTEM FOR IRREGULAR SEAS

```
//PROGRA JOB (????,0356),'RESEARCH',CLASS=B
//*MAIN ORG=NPGVM1.????P
// EXEC FRTXCLGP,IMSL=DP,REGION=1024K
//FORT.SYSIN DD *
C  IN ORDER TO PERFORM SIMULATION ONLY WHEN GAINS
C  HAVE BEEN OBTAINED.
      DIMENSION XX(5)
C  OPTIMAL GAINS FOR CONTROLLER
      XX(1)=2.45967680
      XX(2)=88.2797241
      XX(3)=50.5678864
      XX(4)=5.27039050
      XX(5)=95.3189392
C  THE SUBROUTINE PLANT SIMULATES THE SL-7 CONTAINERSHIP
      CALL PLANT(XX)
      WRITE(6,25)
25  FORMAT(1X,'OPTIMAL GAINS',/)
      DO 30 I=1,5
30  WRITE(6,40)I,XX(I)
40  FORMAT(1X,'XX(',I2,')=' ,F14.7)
      STOP
      END
C
C  SUBROUTINE PLANT(XX)  SIMULATES THE SHIP
      SUBROUTINE PLANT(XX)
      COMMON TDIFF
      REAL*8 L,L2,L3,L4,L5,L6
      REAL*8 X,XDOT,Y,YDOT,U,UDOT,V,VDOT,YAW,R,RDOT
      REAL*8 TIME,ETIME,XUDOT,XUU,XVR,XVV,XDD
      REAL*8 YV,YR,YD,YVVR,YVRR,YVVV,YRRR,YDDD,YVDOT
```

```

REAL*8 NV,NR,ND,NVVR,NVRR,NVVV,NRRR,NDDD,NRDOT
REAL*8 RHO,IZ,FX,FY,MZ,XP,MASS,DELT
REAL*8 DYAW,YAW,YAWC,ISE,ISR,LAMDA,D
REAL*8 K1,T1,T2,D,X2,DX2,S,CH(11),DX3,X3,X4
DIMENSION XX(5)

```

C

C CLOSE LOOP ANALYSIS WITH FILTER

C

C INITIAL CONDITIONS FOR INTEGRATION

C SIMULATION END TIME IN SECONDS

```
ETIME=600.
```

```
TIME=0.0
```

```
ICOUNT=1
```

C INITIALIZE THE COST FUNCTION

```
ISE=0.0
```

```
ISR=0.0
```

```
TDIFF=0.0
```

```
LAMDA=4.2
```

C GAIN COEFFICIENTS

```
K1=XX(1)
```

```
T1=XX(2)
```

```
T2=XX(3)
```

```
T3=XX(4)
```

```
T4=XX(5)
```

C X,XDOT,Y,YDOT ARE FIX COORDINATES ON EARTH

```
X=0.0
```

```
Y=0.0
```

```
XDOT=0.0
```

```
YDOT=0.0
```

C U,UDOT,V,VDOT ARE FIX COORDINATES ON SHIP

```
V=0.0
```

```
UDOT=0.0
```

```
VDOT=0.0
```

```
YAW=0.0
```

```
R=0.0
```

```

        RDOT=0.0
        YAW=0.0
C   ORDERED SPEED IN FEET/SEC
C   54.01 FT/SEC=32 KNOTS
        UC=38.81
C   AT STEADY STATE ACTUAL SPEED (U) = COMMAND SPEED (UC)
        U=UC
C   D = RUDDER ANGLE
        D=0.0
        L=880.5
        L2=L**2
        L3=L*L*L
        L4=L*L3
        L5=L*L4
        L6=L*L5
C   SEA DISTURBANCE
C   FORCES IN X,Y DIRECTION COMPUTED IN FORCES
C   MOMENTS IN Z
        FX=0.
        FY=0.
        MZ=0.
C   ISEA IS A SWITCH; ISEA=0(CAL WATER)ISEA=1(SEA STATE)
        ISEA=1
C   HYDRODYNAMIC COEFFICIENTS ARE INSERTED HERE AS
C   PARAMETERS.
        RHO=1.9876
        MASS=(.0044)*(.5*RHO*L3)
        IZ=(0.00028)*(.5*RHO*L5)
        YAWE=0.0
        X2=0.0
        DX2=0.0
        X3=0.0
        DX3=0.0
        X4=0.0
200 CONTINUE

```



```

      S=DSQRT(U**2 + V**2)
C   INPUT YAW COMMAND
      YAWC=0.0
      IF (TIME.GE.0.0) YAWC=0.0
C   ERROR SIGNAL TO DRIVE RUDDER(YAW ACTUAL-YAW ORDERED)
C   ( COMPENSATOR FILTER )
      YAWC=YAW - YAWC
      DX2=(YAWC-X2)/T2
      X4=K1*(T1*DX2+X2)
      DX3=(X4-X3)/T4
      D=(T3*DX3+X4)
C   AXIAL FORCE HYDRODYNAMIC COEFFICIENTS (SURGE)
C
C   XUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED
C   FOR DIFFERENT ENCOUNTER ANGLE AND SPEED.
C      XUDOT=(-.0001)*( .5*RHO*L3)
      XU=-0.0003*(.5*RHO*L2)
      XVR=(0.0039)*( .5*RHO*L3)
      XVV=(-.0012)*( .5*RHO*L2)
      XDD=(-0.0005)*( .5*RHO*L2*S**2)
C   LATERAL FORCE HYDRODYNAMIC COEFFICIENTS (SWAY)
      YV=(-0.00758)*( .5*RHO*L2*S)
      YR=(0.0023)*( .5*RHO*L3*S)
      YD=(0.00145)*( .5*RHO*L2*S**2)
      YVVR=(0.01)*( .5*RHO*L3/S)
      YVRR=(-0.008)*( .5*RHO*L4/S)
      YVVV=(-0.03)*( .5*RHO*L2/S)
      YRRR=(0.003)*( .5*RHO*L5/S)
      YDDD=(-0.0005)*( .5*RHO*L2*S**2)
C   YUDOT IS THE ADDED MASS TERM WHICH MUST BE CHANGED
C   FOR DIFFERENT ENCOUNTER ANGLE AND SPEED.
C
C      YVDOT=(-0.0039)*( .5*RHO*L3)
      YVDOT=-2304300.00
C   MOMENT ABOUT Z-AXIS HYDRODYNAMIC COEFFICIENTS (YAW)

```



```

NV=(-0.00213)*(.5*RHO*L3*S)
NR=(-0.00105)*(.5*RHO*L4*S)
ND=(-0.0007)*(.5*RHO*L3*S**2)
NVVR=(-0.015)*(.5*RHO*L4/S)
NVRR=(-0.008)*(.5*RHO*L5/S)
NVVV=(0.01)*(.5*RHO*L3/S)
NRRR=(-0.006)*(.5*RHO*L6/S)
NDDD=(0.0001)*(.5*RHO*L3*S**2)
C  NRDOT IS THE ADDED INERTIA TERM WHICH MUST BE CHANGED
C  FOR DIFFERENT ENCOUNTER ANGLE AND SPEED.
C
C  NRDOT=(-0.00027)*(.5*RHO*L5)
NRDOT=-1.5096E+11
C  SETS SEA STATE TO ZERO
  IF (ISEA.EQ.1) GO TO 30
  FX=0.
  FY=0.
  MZ=0.
  GO TO 35
C  UNIT 12 HAS THE SEA STATE DATA NAMED CH
C  IT MUST BE SYNCHRONIZED BY TIME
30  READ (12) CH
    FX= CH(3)
    FY= CH(4)
    MZ= CH(8)
35  CONTINUE
C  U ACTUAL SPEED
C  UC COMMANDED SPEED
C  XP = PROPELLER THRUST
    XP=-XUU*UC**2
C  EQUATIONS OF MOTION
C    UDOT=( (XVR + MASS)*V*R + XUU*U**2 + XVV*V**2
C    1 + XDD*D*D + FX + XP )/(MASS-XUDOT)
    VDOT=(YV*V + (YR-MASS*S)*R + YD*D + YVVR*V**2*R
C    1 + YVRR*V*R**2

```

```

      1 + YVVV*V**3 + YRRR*R**3 + YDDD*D**3
      1 + FY )/(MAS-YVDOT)
      RDOT=( NV*V + NR*R + ND*D + NVVR*V**2*R
      1 + NVRR*V*R**2
      1 + NVVV*V**3 + NRRR*R**3 + NDDD*D**3
      1 + MZ )/(IZ-NRDOT)
C   WHEN TO PRINTOUT
      IF (ICOUNT.EQ.2 ) GO TO 50
      GO TO 300
C   CONVERT RADIANS TO DEGREES
50   YAWDEG= YAW*57.296
      RDEG=R*57.296
      RDDEG=RDOT*57.296
      DDEG=D*57.296
      YAWC=YAWC*57.296
      WRITE (6,100) TIME,YAWDEG
100  FORMAT(1X,F12.8,1X,F12.8)
      ICOUNT=1
C   TEST IF WANT TO STOP
300  IF (TIME.GE.ETIME) GO TO 400
C   INTEGRATION STEP SIZE DELT
      DELT=1.
C   INTEGRATION
      U=U+UDOT*DELT
      V=V+VDOT*DELT
      R=R+RDOT*DELT
      YAW=YAW+R*DELT
      X2=X2+DX2*DELT
      X3=X3+DX3*DELT
C   CONVERT SHIP TO FIXED COORDINATES ON EARTH
      XDOT=U*DCOS(YAW)-V*DSIN(YAW)
      YDOT=U*DSIN(YAW)+V*DCOS(YAW)
      X=X+XDOT*DELT
      Y=Y+YDOT*DELT
      TIME=TIME+DELT

```

```

        ICOUNT=ICOUNT+1
        ISE=ISE + LAMDA*YAWE**2
        ISR=ISR + D**2
        GO TO 200
C  J=TDIFF= COST FUNCTION
    400  TDIFF=ISE+ISR
        WRITE(6,500) ISE,ISR,TDIFF
    500  FORMAT('1',5X,'ISE=',F15.7,'  ISR=',F15.7,'
    1 TOTAL=',F15.7)
        STOP
        END
//GO.SYSIN DD *
/*
//GO.FT12F001 DD DISP=SHR,DSN=MSS.S2160.A211

```

LIST OF REFERENCES

1. Coleman, A.L. and Wang, B.P., Developments in Automatic Control of Ship Steering, Sperry Marine Systems, Charlottesville, Virginia 22906, USA.
2. Garcia, V.C., Optimization of Guidance and Control Using Function Minimization and Navstar/Gps, M.S Thesis, Naval Postgraduate School, Monterey, California, 1984.
3. Cass, J., Theory and Applications of a Sea State Simulation Program, M.S Thesis, Naval Postgraduate School, Monterey, California, 1984.
4. Box, M.J., "A New Method of Constrained Optimization and a Comparison with Other Methods", Computer Journal, pages 45-52, April 1965.
5. Reid, R.E., Improvement of Ship Steering Control for Merchant Ships, Phase IIA, National Maritime Research Center, Kings Point, New York, 1978.
6. Reid, R.E., Design of an Automatic Steering Control System for Ships to Minimize Added Resistance Due to Steering, PHD Dissertation, University of Virginia, 1978.
7. Reid, R.E. and Moore, J.W., "A Steering Control System to Minimize Propulsion Losses of High-Speed Containership, Part I Systems Dynamics", Journal of Dynamic Systems, Measurements and Control, January 1980.
8. Norbbin, N.H., On the Added Resistance Due to Steering on a Straight Course, 13th ITTC Report of Performance Committee, 1972.
9. Michel, W.H., Sea Spectra Simplified, Marine Technology, January 1968.
10. Comstock, J.P., Principles of Naval Architecture, The Society of Naval Architects and Marine Engineers, 1967.
11. Dines, W.S., The Design of Microprocessor Propulsion Control System, Hawker Siddely Dynamics Engineering Ltd(UK).

INITIAL DISTRIBUTION LIST

| | No. | Copies |
|--|-----|--------|
| 1. Library, Code 0142 Naval Postgraduate School Monterey, California 93943 | 2 | |
| 2. Defense Technical Information Center Cameron Station Alexandria, Virginia 22314 | 2 | |
| 3. Hellenic Navy General Staff Geniko Epiteleio Naytikoy Stratopedo Papagou Athens, Greece | 1 | |
| 4. Professor George J. Thaler, Code 62Tr Department of Electrical and Computer Engineering, Naval Postgraduate School Monterey, California 93943 | 5 | |
| 5. Professor Alex Gerba Jr., Code 62Gz Department of Electrical and Computer Engineering, Naval Postgraduate School Monterey, California 93943 | 1 | |
| 6. Department Chairman, Code 62Rr Department of Electrical and Computer Engineering, Naval Postgraduate School Monterey, California 93943 | 1 | |
| 7. LT. Kyritsis-Spyromilios Pericles H.N. Sarantaporou 125, Papagou Athens, Greece | 8 | |
| 8. LT. Horianopoulos Emmanuel H.N. Travlantoni 39, Patisia Athens , Greece | 1 | |
| 9. LT. Horianopoulos George H.N. Panourgia 4, Piraeus Piraeus , Greece | 1 | |
| 10. Mr George Curry Henschel 9 Hoyt Drive, P.O BOX 30 Newburyport, Massachusetts 01950. | 1 | |
| 11. Mr John Carter Henschel 9 Hoyt Drive, P.O BOX 30 Newburyport, Massachusetts 01950. | 1 | |

- | | | |
|-----|---|---|
| 12. | Mr Petros Lemonidis Peloponnissou 4, Pefki, Athens, Greece | 1 |
| 13. | Dr. Robert E. Reid University of Illinois 144 Mechanical Engineering Building 1206 West Green Street Urbana, Illinois 61801 | 1 |
| 14. | LT. Garcia Vicente, USN P.O. BOX 985 Antony, New Mexico 88021 | 1 |
| 15. | Tayfun Tansan Goztepe Istasyon Cad. No:31/13 Istanbul, Turkey | 1 |

Thesis

S66892

Spyromilios

c.1

Development of cri-
teria for automatic
steering.

19 MAY 87

33307

Thesis

S66892

Spyromilios

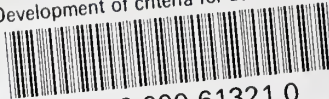
c.1

Development of cri-
teria for automatic
steering.



thesS66892

Development of criteria for automatic st



3 2768 000 61321 0

DUDLEY KNOX LIBRARY